THE

GUIDE-FRAMING OF GASHOLDERS

AND

STRAINS IN STRUCTURES CONNECTED WITH GAS-WORKS.

THE

GUIDE-FRAMING OF GASHOLDERS

AND

OTHER PAPERS

CHIEFLY RELATING TO

STRAINS IN STRUCTURES CONNECTED WITH GAS-WORKS.

BY

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Reprinted from the "JOURNAL OF GAS LIGHTING," *&c.*

FULLY REVISED AND CORRECTED BY THE AUTHOR, WITH MANY ADDITIONS.

London:

WALTER KING,

OFFICE OF THE "JOURNAL OF GAS LIGHTING," &c.

11, BOLT COURT, FLEET STREET, E.C.

1889.

gift

PRINTED BY
KING, SELL, AND RAILTON, LTD.,
12, GOUGH SQUARE, AND 4, BOLT COURT,
FLEET STREET, LONDON, E.C.

PREFACE.

In response to the frequently expressed wish of many of the most eminent gas engineers of the day, the author has collected some of the more important of his writings relating to the construction of, and the strains upon, the principal apparatus in gas-works. Scattered as the papers were in the pages of the "Journal of Gas Lighting," they were unavailable for ready reference. It is hoped, therefore, that in the compact form in which they are now presented, they may prove of more service to the gas engineering profession generally.

The greater part of the book treats of gasholders, as being, from an engineering point of view, the most important iron structures on gas-works. It is assumed that the reader has a somewhat intimate and practical acquaintance with the construction and purpose of gas-works apparatus; therefore, mere description or definition of technical terms is purposely avoided.

The diagrams are merely skeleton outlines, sufficient for the elucidation of the strains on the structures treated of; and are more useful for the purpose than intricate sketches teeming with detail.

Although a great deal has been written and said upon gasholders,* yet the author thinks himself justified in claiming that this is the first attempt to put in a reliable, practical, and *handy* form, the nature and method of determining strains in those very complicated structures. The rules given and the calculations involved are

* In this connection, special mention must be made of the report of Mr. B. Baker, M. Inst. C.E., on the strains upon the South Metropolitan gasholder in the Old Kent Road, as given in the "Journal of Gas Lighting," Vol. XXXVII., p. 141.

arithmetical problems of the simplest kind; and a difficult study in itself is thus presented in the easiest possible light.

Much might be said upon the history of gasholder construction: The gradual development of gasholders from a few feet in diameter to the mammoth structure at East Greenwich, erected in 1888 by Mr. George Livesey; the various fashions and tastes that have prevailed; the decline of the old columnal system, and the gradual advance and acknowledgment of the cylindrical principle of guide-framing, first introduced by Mr. Livesey, in 1878, at the Old Kent Road; the *partial* abolition of guide-framing, as proposed by Mr. Livesey as long ago as 1881 (a gasholder constructed on this principle has been working since 1887 at Rotherhithe); and, finally, the proposed *entire* abolition of guide-framing—first suggested, by Mr. W. H. Y. Webber, in 1887—shortly to be tested by practical working on Mr. Gadd's principle, at Northwich.

> This latter proposal—viz., the entire abolition of guide-framing—can only be made possible of success by adopting a special arrangement of tank-guides and bottom rollers, such as will secure a *perfectly level and rigid base* for the holder as it rises and falls.
>
> Since the papers contained in this volume (which, of course, refer to vertical guides only) were written, various schemes have been devised to accomplish this primary and essential condition; Mr. Gadd leading the way in August, 1888, with his inclined or *spiral* tank-guides, followed closely by Mr. Livesey, Mr. Terrace, and Mr. Pease.
>
> Presuming that the *perfectly level* working and *rigid base* can be secured, there is still to be considered the tendency of the holder to distort out of the cylindrical form horizontally, which must be met by increased strength, considerably beyond what is usual, in the framework of the holder.

These points will be decided on a practical scale, for gasholders of small size and of two lifts only, when Mr. Gadd's gasholder at Northwich has been subjected to the test of the strongest wind. It must not only successfully resist destruction and over-straining, but work healthily with but a reasonable amount of wear and tear, when subject to the vicissitudes of gasholder life.

These few remarks on the growth of gasholder construction, although somewhat digressive, are sufficient to show the great interest taken in this fascinating subject by gas engineers.

The papers referring to the strains on purifiers are, I believe, the only ones of the kind published.

In preparing the articles for the present work, the Author has taken the opportunity of revising the whole—correcting and extending them where necessary, and of adding much new matter. He trusts, therefore, they may be found worthy of a continuance of the favour which has already been accorded to them.

F. S. C.

SUTTON, SURREY, *October*, 1889.

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ERRATA, ETC.

PAGE 1.—Line 2 from bottom, for "1888" read 1882.
„ 6. „ 6 „ top, for "at" read through.
„ 17. „ 8 „ bottom, for "This" read which, and omit the full stop.
„ 19.—Fig. 13 should show the top roller on the left-hand side bearing *against* the guide-framing, and the top roller on the right-hand side *off* the same.
„ 19.—Line 5 from top, for "F and F" read F and F_1.
„ 21.—Formula at the foot of the page should read—

$$\frac{(4d^2 + \cdot 165\, D^2) \times 11\, D}{7 \times 2d} \text{ or roughly } \frac{3d^2\, D + \cdot 14\, D^3}{d}$$

„ 28, 29, and 31.—Instead of Strain Scale "1/4″ = 1′ 0″" read 1/4″ = 1 ton.
„ 29.—Line 2 from top, after = read to.
„ 32. „ 11 „ bottom, column 4 in table, for ·2 read 2.
„ 37.—Top line should be followed by "of cantilever type."
„ 39.—Paragraph III. should be entitled "Strains in Standard Due to Tendency of Structure to Distort."
„ 45.—Line 6 from top, for "A" read A_1.
„ „ Lines 10, 11, and 12, after the formulæ, for "$= A_1$" read $= A$.
„ „ Line 19 from bottom, in the formula "6720" should read 6720 n; and in this and the two preceding formulæ "$= A_1$" should read $= A$.
„ 46. „ 17 from top, put a bracket after "others)."
„ 48. „ 14 „ „ for "d_2" in the formula read d^2.
„ „ „ 4 „ bottom, for "B_1" at beginning of line read B.
„ 50. „ 4 „ top, for "tiers" read ties.
„ 51. „ 12 „ „ for "or" read of.
„ „ „ 17 „ „ for "junction" read junctions.
„ 52. „ 12 „ „ for "stiffeners" read stiffness.
„ 56. „ 16 „ „ formula should read

$$W = \frac{r^4 - r_1^4 \times \cdot 7854\, C.}{r\, L}.$$

„ 59. „ 9 from bottom, for "Fig. 29 C." read Fig. 29 B.
„ 61.—After line 13 from top, read "Standards of Section, Fig. 29 E, page 50."
„ 62.—Line 21 from top, after fig. 29 D read, "See page 50."
„ 64. „ 11 „ „ after 3·7 put capital S for Sectional.
„ 66. „ 10 „ bottom, formula should read $\frac{A\, d_1}{1 \cdot 6}$.
„ 68. „ 5 „ top, for "lists" read lifts.
„ 69. „ 14 „ bottom, after "lift" read working up the outside of middle lift.
„ 75. „ 15 „ bottom, for "F" read S.
„ 78. „ 6 „ top, for "press" read pressure.
„ „ „ 9 „ bottom, after "p" in the formula, put the sign × instead of +.
„ 78.—In the two formulæ at the foot of the page, substitute S for s.
„ „ The formula preceding "check proof" should read $\frac{(a^2 + b^2)\, p}{4\, b} = S$.
„ „ Line 9 from bottom, in the formula the bracket under "diam. of sphere" should not embrace the "2" in the numerator.
„ 80.—Line 16 from top, after "w" read (by.
„ 90.—In fig. 4, the two short dotted lines on each side of d should be the arcs of circle struck from A and A.
„ 91.—Line 8 from bottom, for "that" read than.
„ 93. „ 14 from top, for "(R)" read (B).
„ 97. „ 20 „ „ after "such" read a.
„ 106.—Lines 17 and 18 from bottom, omit the comma after "span," and put a line dividing the *numerator* from the *denominator* in the next formula.
„ „ Line 6 from top, for b^2 in the denominator of the formula read b^4.
„ 109. „ 2 „ bottom, for d read d^3 in formula.
„ „ „ 3 „ „ for $\frac{0 \cdot 001 + a^2\, d\, x}{D c}$ read $\frac{\cdot 01 \quad a^2 \quad d \quad x}{D\, c}$.
„ 112.—For the formula at foot, read $\frac{S - \sqrt{S^2 - a^2 p^2}}{p.} = b$
„ 115.—Line 7 from bottom, omit comma after "use."
„ „ Formula (4) should read $\frac{(a^2 + b^2)\, p}{4\, b} = S$.
„ „ „ (5) „ „ $\frac{2\, S - \sqrt{2\, S^2 - a^2 p^2}}{p} = b$

THE GUIDE-FRAMING OF GASHOLDERS.

IN the four following articles, it is assumed that the reader is somewhat acquainted with the construction of gasholders, together with the names applied to their various parts. It would be contrary to the writer's intention to enter into any elaborate elementary treatise on the details of design or manufacture. Not only would it overburden and confuse the matter contained in the articles, but it is information readily accessible to any practical engineer connected with the design and manufacture of gasholders.* The object of these papers may, therefore, be stated briefly to be as follows :—

(1) To show, in the simplest possible manner, the principles relating to strength of gasholders, and the manner in which they are affected by varying the design.

(2) To give ready rules for determining the strains on the guide-framing for gasholders under different conditions ; also the floating holder, as far as it is affected by alteration in the guide-framing.

(3) To show the extent to which the present-guide-framing can be modified as regards height; and the advantage or disadvantage likely to result from such practice.

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* In this connection, reference may be made to the description and working drawings of the Sydney Gasholder, which are now to be had in pamphlet form. As the *Journal of Gas Lighting* has remarked, there is nothing particularly original about the general design of this gasholder ; it is an example of ordinary modern practice, but with this additional advantage—the drawings given are the drawings which were actually used in the shops by the workmen, *everything* necessary for the actual *making* of the holder being shown thereon.

The following descriptions and drawings of practical gasholder work may also be consulted :—

Mr. G. Livesey's Description and Drawings of the South Metropolitan Gasholder, Old Kent Road.

Mr. G. Livesey's Paper on the Principles of Gasholder Construction. (*See* Transactions of The Gas Institute, 1888.)

Mr. Charles Hunt's Description and Drawings of the two large Gasholders at Birmingham.

FIRST ARTICLE.

STABILITY.

THE question of guide-framing to gasholders is not one that can be dealt with exhaustively in a single article. Guide-framing varies so much in form, and the conditions under which it acts are likewise so variable, that the present article does not pretend to determine the actual strain upon each of its parts, severally and in detail but rather treats of the stability of the structure as a whole.

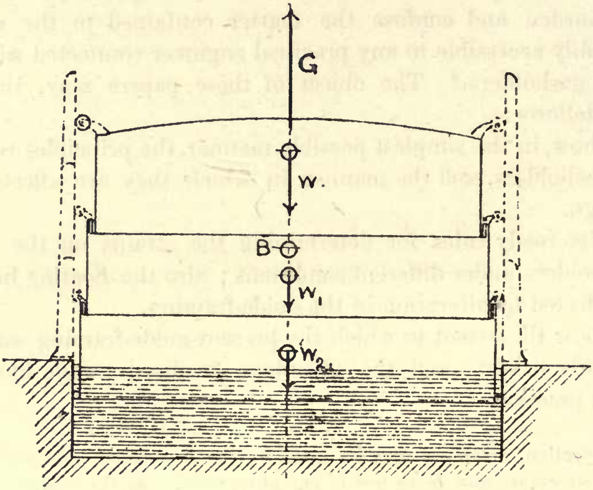

FIG. 1.

Let fig. 1 represent a telescope gasholder, in section, and in its normal condition—that is, not acted upon by the tilting forces wind and snow. The forces acting upon the gasholder when floating, as shown in the diagram, are :

(1) The weight of each of the lifts—viz., W W_1 and W_2 respectively. The weight of each is assumed to be concentrated at its centre of gravity, and acts vertically downwards, as shown by the arrows.

(2) The total lifting pressure of the gas G. This is, of course, equal to the sum of W W_1 and W_2, and acts vertically upwards, through the centre of buoyancy. The centre of buoyancy is on the vertical line passing through W W_1 and W_2, as long as the gasholder remains *vertical.* It is situated about midway between the crown of the holder and the water-level in the tank.* The pressure of the gas on the sides is, of course, self-balancing.

These forces, it will be noticed, hold the body in equilibrium as long as the axis is vertical, as they then balance one another. The equilibrium is unstable, however; for the addition of another force sideways, however slight, would upset it—the centre of gravity of the holder being above the centre of buoyancy.

But omitting for the present the upsetting forces—wind and snow—it would at first sight appear that the holder would rise and be sustained in equilibrium without any guide-framing at all. Indeed, *theoretically,* it would rise and work without even any rollers or guides of any kind; but this would entail impossible conditions—viz. (1) That each lift should in itself be perfectly rigid; (2) each lift should be perfectly balanced, not a pound more weight one side than the other; (3) frictionless working and perfect fit. None of these conditions exist, or ever will exist perfectly, in any gasholder. A holder may be practically rigid, and each lift may for all intents and purposes be in balance, and the friction due to pressure of rollers (assuming there are rollers) more on one part than another—caused by (1) uneven path; (2) guides out of the vertical; (3) rollers put closer up to work in one point than another; and (4) binding of axles in some places—may be reduced to a minimum; but if these defects exist ever so slightly, there is a tendency to *tilt.* If there is nothing to meet and balance this tendency to tilt, it will tilt; and when once it starts tilting, the tendency to tilt increases—the conditions which then arise becoming more and more unfavourable for preserving equilibrium. [See Note A, page 9.]

It is therefore absolutely necessary to have guiding and controlling power over the holder, even supposing the foregoing forces to be the only ones acting upon it. The extent of guide-framing necessary would appear, at first sight, very slight to overcome this, but the cup rollers inside, working against gasholder sides, and the bottom rollers working against the side of the tank, are, by themselves, inadequate to preserve the vertical working of the holder. The bottom rollers only touch the tank guides on one horizontal circle, in one plane—as regards contact with the guides—and as one circle

* It has been stated that the *centre of buoyancy* is at a point very much lower down the axis—almost to the water-level. Fig. 3 (page 10) would seem to favour this view; and no doubt it is more strictly accurate. It is of very little account, however, as it scarcely touches the question; and where it does affect the conclusions arrived at in this article, it is only to more strongly enforce them.

will revolve within another of equal size on its diameter without cutting it, it is evident that one-half of the bottom rollers can, by the tilting of the holder, fall away, and the other half rise away from contact with the guides; the gasholder swivelling, as it were, on two rollers diametrically opposite. There is therefore practically no resistance to tilting. To get this, there must be two tiers of rollers to each lift of the gasholder, one above the other, running in the guides. The tilting can then only take place just so far as the play in the rollers, or the elasticity of the structure, will allow. This, however, is by no means an insignificant item. It is impossible to get perfect roller-contact, *constantly*, for all positions of the holder. They would have to be very close up and tight (which very tightness carries its own evils with it). There is almost bound to be $\frac{1}{8}$-inch play here and there at least; and apart from structural defects, variations in temperature will alone effect more difference than this. This would admit of a large gasholder getting 2 or 3 inches out of level, even supposing the rollers were 20 feet from tier to tier. When you add to this certain 2 or 3 inches, the extra amount due to the elasticity of the structure either in its own framing or the external guide-framing, the spring of carriages, the racking at joints, and above all the strain caused by the leverage of the tower of lifts *above* (without any side support), this 2 or 3 inches is more likely to develop into 8 or 9 inches. As excessive wear, due to abnormal strain, is brought to bear upon the roller axles and all working parts, the friction and play is increased, and ultimately the destruction of the holder necessarily follows.*

It is well known amongst experienced gasholder makers who have had occasion to build very shallow gasholders, that it is not possible to make them work at all, unless the depth of each lift exceeds one-seventh of the diameter, without throwing in an immense amount of material to get rigidity and strength to resist the enormous tilting tendency, even without considering the effect of wind or snow acting upon them. It is better, however, to make the limit of shallowness, as Mr. Livesey says, one-fourth or (at the outside) one-fifth of the diameter.

From the foregoing we may draw the following conclusions :—

(1) That gasholders cannot work at all without at least two tiers of rollers to each lift; thereby necessitating guide-framing.

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* Much of the above would appear self-evident, but so much misunderstanding has been expressed on this subject that I have discussed it somewhat fully. For more on this question of play in bottom rollers, tilting scope, elasticity of structure, &c., see Mr. G. Livesey's letter in the *Journal of Gas Lighting* for April 26, 1887, the discussion on Mr. W. H. Y. Webber's paper at the meeting of The Gas Institute in Glasgow, Mr. W. Gadd's article on "The Guide-Framing of Gasholders" (*Journal*, Vol. L. p. 331), and subsequent correspondence in the *Journal*—more particularly my letters of Aug. 30 and Sept. 13, 1887, and Aug. 14, 1888, signed "Theory and Practice."

(2) *That single-lift gasholders cannot work safely without sufficient depth of guide-framing.*

(3) *That unless the depth exceeds one-seventh of the diameter, much waste of material is necessitated.*

(4) *That a telescope gasholder is even worse, unless the guide-framing exceeds one-seventh of the diameter in height, owing to lever tower.*

(5) *Even without wind pressure or weight of snow, the above is true—much more so with.*

SHORT GUIDE-FRAMING.

We will now pass on to the consideration of gasholders with only partial guide-framing—*i.e.*, the guide-framing not carried higher than the outer lifts, and the inner lift rising above the top of the guide-framing when the gasholder is fully cupped.

Hitherto we have not considered the effect of wind or snow, because the points could be proved without calling them to our aid. Now, however, we will assume that the guide-framing is sufficiently high (say, not less than one-fourth the diameter of the gasholder) to insure safety from tilting dangerously from any of the causes previously considered.

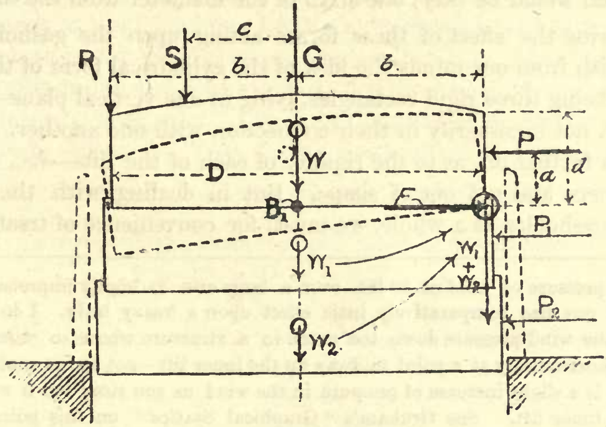

Fig. 2.

The question now assumes a more complex character; but it can be elucidated by the aid of the accompanying diagrams.

Fig. 2 represents a telescope gasholder in section, at its full height, with guide-framing reaching to the top of the middle lift. The arrows indicate the direction of

the various forces acting upon it, which, for convenience, we will enumerate as follows :—

(1) W W_1 and W_2 represent the weights of the inner, middle, and outer lifts respectively, as before described.

(2) G is the total lifting pressure of the gas, which is equal to $W + W_1 + W_2$, and acts vertically at the centre of buoyancy, as before described. G is increased in magnitude, however, when P and S are added to the forces, as will be shown. [See Note B, page 11.]

(3) P = the pressure of wind (total). To be on the safe side, we will take this, after allowing for the cylindrical shape of the holder, &c., to equal 16 lbs. per square foot over the entire diametral section = $D \times d \times 16$ (where D and d represent the diameter and depth of the inner lift) when one lift only is free.* P_1 and P_2 are the pressures of wind on the middle and outer lifts. F is the horizontal reaction to P on inner lift; and is equal to P.

(4) S = the pressure of snow. It is a very dangerous tilting force when it lies on one side of the top, and may possibly equal a mean of 5 lbs. per square foot (say, 1 foot thick) over one-fourth of the area, the centre of gravity of which would be (say) one-sixth of the diameter from the edge of the holder.

In considering the effect of these forces acting upon the gasholder, we may for the present banish from our minds the idea of the cylindrical form of the structure, and look upon it as being three rigid rectangles, lying in one vertical plane—that is, rigid in themselves only, not necessarily in their connection with one another. It is a question to be dealt with further on, as to the rigidity of each of the lifts—*i.e.*, their liability to rack at the corners and get out of shape. But in dealing with the question of the stability of the gasholder as a whole, we must, for convenience of treatment, assume at

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* A *constant* pressure of wind of 50 lbs. over a large area is highly improbable; and an intermittent and local one has comparatively little effect upon a heavy body. I do not think it wise, however, to cut the wind-pressure down too much in a structure where so much depends upon its stability. P acts horizontally at a point midway up the inner lift—not at the centre of gravity of the inner lift. There is a slight increase of pressure in the wind as you rise; but it would not be felt in the depth of the inner lift. [See Graham's "Graphical Statics" on this point; and also Mr. B. Baker's reports on wind pressure at the Forth Bridge. Two gauges registered as follows:—

At a height of	70 ft.	No. 1 gauge gave	12 lbs. per sq. ft. ;	No. 2,	15 lbs.
„	210 ft.	„ „	11 to 15 lbs.	„ „	16 „
„	375 ft.	„ „	15 to 24 lbs.	„ „	14 „

showing a very slow increase (if any) in the pressure as the elevation increases. See also Hutton's Stability of Chimney Shafts.]

the outset that each lift is a perfect structure in itself—perfect as regards maintenance of rectangular form.

Referring to fig. 2, we start with the supposition that the two lower lifts are perfectly rigid, and will not tilt. They are only free to rise and fall in a vertical plane, at the same time remaining perfectly level. Now it can be seen at a glance that if the inner lift tilts, it must do so by turning round the point O, as shown in dotted lines. It is evident the inner lift cannot turn on a diameter like the outer lift, because the whole weight of the middle and outer lifts has to be carried by the inner lift; and as these cannot tilt or rack out of shape (being assumed to be rigid rectangles rigidly guided), their whole weight must be carried from what we may term the swivelling point O, when the inner lift tilts.

Now, in order for the opposite side of the inner lift to fall as shown, the depressing force on that side, R, must exceed the weight hanging on the other. We have seen that the weight hanging at $O = W_1 + W_2$; therefore the heeling or tilting forces must produce when resolved in a vertical direction on the opposite side to O, a depressing force greater than $W_1 + W_2$. In other words, *unless the resolved wind and snow pressure, R, exceeds the weight of the outer lifts, the gasholder cannot tilt on the conditions here assumed.*

To resolve the wind pressure into an equivalent depressing force on the opposite side, we have merely to treat the inner lift as a balanced beam, supported by the gas pressure G anywhere on the vertical centre line (say, at B_1). Then the forces tending to rock the inner lift in one direction must balance those tending to rock it in the other otherwise equilibrium cannot exist. Let B_1 be the point of support, on which the inner lift is supposed to be balanced. Then taking moments round B_1 we have—

$$\frac{P \times a}{b} = \text{depressing force due to wind.}$$

Or, expressing it in terms of the diameter and depth of the holder—

$$\frac{2 \times 16 \times D \times d \times d}{D \times 2} = 16d^2.$$

We have, therefore, a simple rule for determining the stability of the inner lift when cupped—viz., sixteen times the depth squared (in feet) must not exceed the weight hanging on the inner lift (in pounds). But we have likewise to consider the depressing force due to snow. This may be expressed as follows:—

$$\frac{S \times c}{b} = \text{depressing force due to snow.}$$

Or, expressing it in terms of the diameter—

$$\frac{D^2 \times 0{\cdot}7854 \times 5 \times 2 \times D}{4 \times 3 \times D} = \text{(say) } {\cdot}66\ D^2.$$

The maximum depressing force R, adding the effect of wind and snow together, could not therefore exceed $\cdot 66\ D^2 + 16d^2$, which we may term the "resolved wind and snow pressure," referred to in the above rule. [See Note B.]

An example will show the simplicity of the rule. A three-lift holder, 200 feet diameter and 45 feet deep (each lift), has guide-framing reaching to the height of the two outer lifts only. It is required to know whether the inner lift will tilt under the action of the wind and snow. Applying the formula: $(\cdot 66 \times 200 \times 200) + (16 \times 45 \times 45) = 58{,}800$ lbs., or (say) 26 tons. The weight of the two outer lifts would be at least 250 tons, or nearly ten times the tilting force on the opposite side. So, on the assumed conditions, it could not tilt.

Now suppose the guide-frame to reach to the top of the outer lift only, we can still apply the formula, with the difference that we must take d as the depth of two lifts —the inner and middle. Then $(\cdot 66 \times 200 \times 200) + (16 \times 90 \times 90) = 156{,}000$ lbs., or (say) 70 tons. The weight of the outer lift would be about 130 tons at least. On the stated conditions, the gasholder would not therefore *tilt.*

We will take another example—viz., a telescope gasholder, 100 feet diameter, 30 feet deep. Applying the formula: $(\cdot 66 \times 100 \times 100) + (16 \times 30 \times 30) = 21{,}000$ lbs., or scarcely $9\frac{1}{2}$ tons. The weight of the outer lift would equal at least 35 tons; showing, therefore, that the inner lift would not tilt.

In applying the formula to a single-lift gasholder without any guide-framing, $W_1 + W_2$ is always *nil,* because there are no outer lifts. It follows, therefore, that $\dfrac{Pa + Sc}{b}$ must *always* exceed it; and the gasholder would necessarily tilt, even with the slightest side pressure, because any pressure exceeds *nil.*

It is possible to imagine that the gasholder might be tilted by a *sudden* application of the forces wind and snow, before the whole of the weight of the outer lifts can be transferred to the one side. Unless two of the three lifts are without guide-framing, the snow is the greater tilting force; but it is a force which very slowly and gradually increases in intensity. This admits of the holder descending as the load increases, diminishing the volume, but increasing the pressure of the gas in proportion. With the wind, however, we have a very fickle force. It comes more or less in gusts and sweeps; and if severe, it may be difficult for the holder to answer to the fluctuations with the requisite rise and fall. We must therefore consider how this would affect the stability. It is certain that the outer lifts will not remain suspended in the air without anything to support them. The frictional resistance of the rollers and guides will not alone sustain the outer lifts, as it has but little influence over a heavy structure with sufficient wheel-base. They depend, therefore, for their support by hanging on

the inner lift. If the inner lift tends to tilt suddenly, the weight of the outer lift must come just as suddenly all on the one side of it, and pull it down at O; for there is no reason why a heavy structure like the inner lift should answer any quicker to the sudden push of the wind than to the sudden pull of the outer lifts, especially when we know the latter to be the greater force. Again, the frictional resistance (due to form) to the lift tilting, is much greater than the frictional working of the holder up and down in the guides. [See Note C, page 12.] We may conclude, therefore, that in a properly constructed gasholder the sudden application of the upsetting forces wind and snow to the inner lift will not upset it, providing the suspended lifts remain firm and level, and are able to descend freely in the guide-framing.

We have now proved, without doubt, that—

(6) *Under certain conditions, gasholders can be constructed without guide-framing reaching higher than the height of the outer lift. The conditions being: That each lift must be rigid in itself, and unable to distort under the strains induced; tnat the guide-framing must also be rigid and unyielding; and that the holder must be free to rise and fall perfectly level.*

We have also produced simple and reliable formulæ by the application of which the stability of the structure as regards tilting can be determined. It now remains to examine the conditions (referred to above) on which the stability depends, and define the nature of the strains on the several lifts, and their capacity for resisting them.

NOTES.

Note A.

It has been stated that if a gasholder starts tilting, the tendency to tilt increases —that is, forces come into action which have no effect till the equilibrium is disturbed.

The exaggerated diagram fig. 3 (page 10) shows the gasholder acted upon by an upsetting couple, due to displacement of centre of gravity and centre of buoyancy. When tilted as shown, the former is thrown over with the axis. The latter, however, is not necessarily on the inclined axis, but somewhat to the right of it, because the lifting pressure of gas on the left is balanced by the pressure downwards on the part of gasholder immediately below, as shaded in the diagram. On the other hand, the gas not only lifts by pressing on the right-hand side of the crown, but also on the inclined side sheets. The effective centre of vertical force upwards is, therefore,

about in the position marked B (in the centre of volume, to the right of the vertical plane Y);* and as the whole weight acts vertically downwards through W, the two forces G and W form an upsetting couple, which increases in magnitude as the gasholder inclines more and more—that is, in the same ratio as the lever arm x increases. The magnitude of the upsetting force is, of course, measured by the weight of the gasholder, multiplied by the distance x. It will be seen, after tilting commences, what a powerful effect this has, and what little chance the gasholder has to right itself, even though the original or primary cause of the tilting be removed. It can only do so by reason of the elasticity of the guide-framing, together with its own elasticity, enabling it to rebound, just as a compressed spring, or a deflected girder will recover itself after the weight is removed.

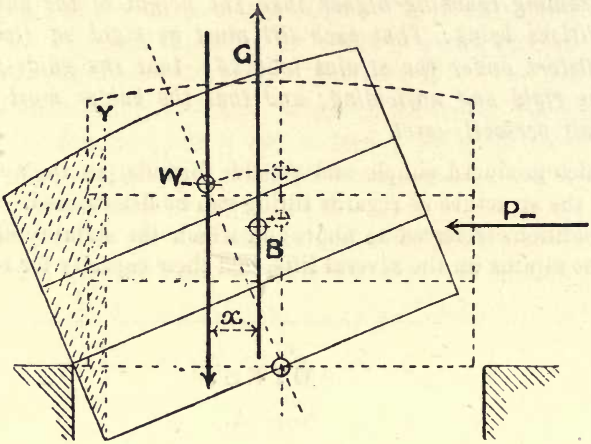

FIG. 3.

If a gasholder tilts so much that the gas can escape under the curb, there is little chance of it righting itself; because, the lifting or suspending force being removed, the dead weight of the whole gasholder falls, not having anything to support it, and so becomes a complete wreck.

We may conclude, therefore, that tilting to any extent is not to be permitted. In large gasholders with reduced guide-framing, the drop on one side should not in any case exceed (say) 3 inches, under all forces and conditions.

---

* See previous note on this.

NOTE B.

The substitution of R (in fig. 2) for the tilting forces S and P is quite correct as far as the treatment of the subject in this article is concerned, and is done so, to present the conditions of stability in the simplest possible light. But when we come to consider the effect of the forces in straining the holder, we must take P and S in their proper positions. R will then represent the weight to be applied at O to prevent the inner lift tilting, and which, of course, is derived from $W_1 + W_2$. Thus—

The forces P and S tend to rotate the body round B_1 from right to left. We must therefore find the weight required to act downwards at O to resist the tendency to *lift* on that side, and so prevent the tilting which would otherwise take place. If we take B_1 as the supporting point, then the moment of the forces tending to rock the beam to the right are $Pa + Sc$. The force required, therefore, to balance this at O will equal $\frac{Pa + Sc}{b}$, which, as before stated, is equal to R.

It should be noted that, although we take moments round B_1 it does not necessarily follow that B_1 is *stationary*. Otherwise the point O would rise when tilting took place, lifting the outer lifts with it. The effect is the same, as regards stability, if we imagine O to be stationary and B_1 to fall. Of course, both points descend as the gasholder descends bodily (through the tilting forces compressing the gas); and probably O would come to rest first, and B_1 go on as the inner lift tilted.

The increase of gas pressure is that due to the weight of snow only. As P acts *horizontally*, it does not affect the *resultant* gas pressure (which acts vertically), although it influences the disposition of the forces, transferring a part of the weights of the outer lifts to O, but not adding to the resultant gas pressure, which is therefore $S + W + W_1 + W_2$.

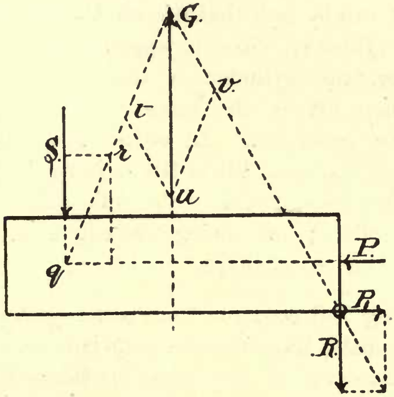

FIG. 2*a*.

The effect of the wind and snow upon the inner lift, together with the resultant force transmitted to the outer lifts may be shown graphically by the following simple diagram:—

In Fig. 2*a*, let P = wind, and S = snow. Produce P and S to intersect in *q*; and then by parallelogram of forces determine their resultant at this point—viz., *q r*. Produce *q r* to intersect the centre line G. Join G O. Make G *t* = *q r*, and, parallel to G O, draw *t u*. Then G *u* represents the pressure of gas

due to wind and snow, and G v set off equal to $t\ u$, and, applied at O, is the resultant force required to hold the inner lift in equilibrium, when acted upon by the wind, snow, and gas as per diagram.

Now, it is clear that this resultant can be split up into two components at O, one horizontal, the other vertical—viz., P_1 and R.

It will be found, on drawing the diagram to scale, that the result agrees exactly with what we have already determined.

Note C.

The inner lift also receives assistance from the following ;—As before stated, the inner lift must revolve round the point O in order to tilt. This is, in reality, one of the cup rollers which are in one circle around the cup, and their points of contact are a tangent circle. In other words, we may look on it as two coinciding circles. Now, if a circle be tangent to the interior surface of a hollow cylinder, it cannot revolve round its point of contact with the cylinder without intersecting the cylinder; and the nearer the diameter of the circle approaches that of the cylinder, the less the movement that can take place before intersection occurs. This can be illustrated by a diagram.

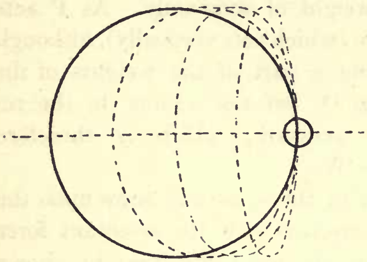

Fig. 4.

In fig. 4 the thick circle denotes the cylinder, the series of ellipses show the plan of the circle in contact with it at O. As it revolves around this point, it can be seen that the circle cuts the sides of the cylinder. Now, in applying this to the gasholder, the cylinder is the outer lift, and the inner lift is the circle of the cup rollers on the inner lift. In order, then, for the one side of the inner lift to fall as in fig. 2, it must, if the rollers be in perfect contact with the guides, do one of the following :—(1) Intersect the gasholder; (2) break off the rollers; (3) spring the cup out of circular shape; or (4) spring the sides of the outer lift out of shape.

Now (1) could not take place till after tilting had occurred from other causes; (2) might possibly happen; and (3) and (4) would probably happen under sufficient strain to a limited extent; but very little elasticity is sufficient to tilt the holder considerably, apart from the certainty that there will be play in the rollers sooner or later.

It may be necessary to mention that the operation of tilting the inner lift in the outer one is a very different thing from the tilting of the whole gasholder in the tank. The bottom curb of a gasholder is free to rise on the one side and fall on the other—turning on a diameter; but not so the cup of the inner lift. That has the weight of the outer lifts to carry, and therefore cannot revolve on a diameter, but on a single point situated on the circumference—the weight of the outer lifts being slung, as it were, from that point.

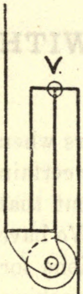

FIG. 5.

There is likewise assistance rendered against tilting by the stiffness of the cup plates, which are held by friction at the top—due to the weight of the outer lifts at V (fig. 5), and at the base by the cup rollers. This reverse-leverage must, of course, be overcome before the inner lift could tilt. It can be augmented, too, by the addition of outside rollers on the grip, working against outside guides on the inner lift. These are trifling aids to stability; but they help in the right way, and tend to make the holder secure.

SECOND ARTICLE.

STRENGTH AND RIGIDITY OF GASHOLDER BELL WITH VARIOUS HEIGHTS OF GUIDE-FRAMING.

The first article was devoted to the investigation of the stability of gasholders when acted upon by the tilting or heeling forces wind and snow. We found that, under certain conditions, it would be quite safe to abolish guide-framing to the upper lifts; but that in no case should the guide-framing be of less height than the outer lift. We have now to consider whether it be possible to comply with these necessary conditions for stability—viz.: (1) That each lift must be rigid, and capable of resisting the racking strains due to the particular forces acting upon it; and (2) The guide-framing must be perfectly stable, and at all times preserve the level working of the holder.

RIGIDITY OF GASHOLDERS.

The racking strains on each of the lifts are, of course, due to the tilting forces wind or snow, or both. If there be no pressure of wind or snow, the racking strains on the holder are theoretically *nil;* but, on the other hand, if they are sufficient to cause *tilting* of one or more lifts, they are at a maximum. Between these two extremes—viz., equilibrium and tilting—there are the various degrees of *tendency* to tilt. It is under the latter heading that all practical cases will come.

It will be convenient to deal separately with each of the lifts.

INNER LIFT.

When the inner lift is unsupported by guide-framing, the racking force is equal in magnitude to $\frac{1}{2}$ P (or 8 D*d*.) acting horizontally on a level with the top curb. The base of the inner lift—*i.e.*, the cup—is level and firm, and may be looked upon as the fixed end of a cylindrical cantilever; the load being applied at the end, and tending to distort the figure, as shown in fig. 6. The cup of the inner lift is preserved level by the weight

of the outer lift, as already explained in the first article; the outer lift being rigid, and kept vertical by the guide-framing. The resistance to bending is from the top curb, cup, sheeting, and vertical stays, forming together a kind of circular plate beam. The top curb and cup form the stiffeners; the vertical stays are the flanges; and the side sheeting is the web. It is much in the same conditions as it would be if it were standing on the level ground, and acted upon by the distributed wind pressures.

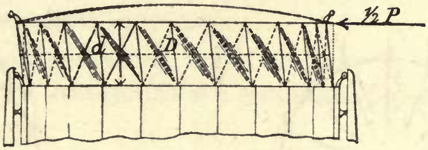

FIG. 6.

NOTE.—It is, of course, understood that the several forces, represented by the arrows in these articles, are not actually single and isolated pressures concentrated at single points on the structure, but that they are the resultants of several forces distributed over the same, which latter are, for more convenient treatment, considered as concentrated at their different centres of pressure, just as we may consider the weight of a body as concentrated at its centre of gravity. Hitherto we have been dealing with the conditions of equilibrium of the whole gasholder, and resultants of distributed forces have alone been used. Precisely the same results would, however, be obtained by splitting up each resultant into its component forces, and using them instead; only it would be a tedious mode of proceeding. This method of taking the resultant instead of the several component forces is quite correct when we are considering the stability of a structure *as a whole;* but when it is desired to treat of each part of the structure in detail, we must consider the local effect of the component forces instead of the single resultant. Take, for instance, the force ½ P in fig. 6. This force is not actually concentrated here; it really represents the distributed wind pressure on the side of holder. [See Note D, page 24.]

Now we come to deal with the rigidity of each of the lifts in all their parts, it becomes necessary, of course, to bear in mind the cylindrical form of the holder, and to notice the local effects of these distributed pressures.

Fig. 7 represents a plan of the inner lift, which is pressed upon (1) by the pressure of gas from within, acting radially outwards and of uniform intensity, as shown by the arrows *g g;* (2) by the wind from without, acting all on one side, *p p;* and (3) the pull of the top sheets *s s*. (The wind and gas pressures are distributed at the vertical posts.) A glance at the diagram is sufficient to show that these forces are to an extent balanced; *g g*, would appear to be met by *s s*. But it must be remembered that they do not act in the same plane—*g g* are distributed over the whole depth of the sides; whereas the pull of *s* is on the top edge only, and can therefore only affect the sides below, when the curb yields to compression.

Disregarding for the moment the pull of the top sheets, and taking only the gas and wind pressures, which are distributed over the full depth of the side sheeting, we get a diagram as in fig. 8. Now, by substituting the resultants for those forces acting at the same points, we have a diagram as in fig. 9; showing clearly that the gas pressure is partly neutralized by the wind pressure on the wind side. But it will be noticed that the pressures of gas on the opposite side (away from the wind) remain as

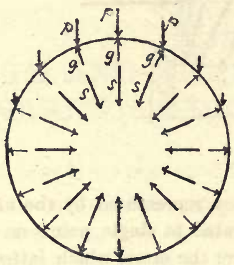

FIG. 7.

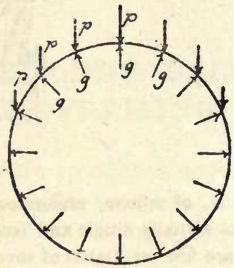

FIG. 8.

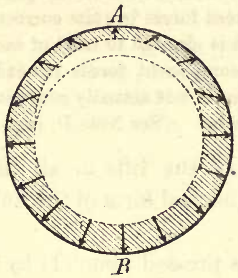

FIG. 9.

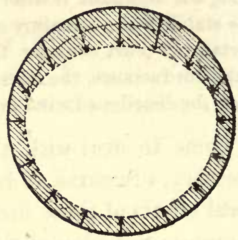

FIG. 10.

before. Therefore the latter have a tendency to drive the holder along; so that it would appear that the holder is pushed over by the gas pressure on one side, through the wind neutralizing it on the other. [See Note E, page 25.] At the same time, the unbalanced gas pressure on the one side tends to draw the sheeting round from the other—*i.e.*, from A to B—flattening the side locally. This is a reason for attaching the side sheeting to the vertical stays all the way up, as it prevents the possible sliding or movement of the

sheeting over the vertical stays, and makes every stay take its full share of the work. So much for the distorting influence of the wind over the side sheeting. But these forces are transmitted by the vertical stays to the top curb above and to the cups below. They are equally divided between these two rings. (See Note F, page 25.) Fig. 10 shows the effect of all the forces on the top curb, including the pull of the top sheets. It will be noticed they have a tendency to pull the curb in on the wind side, and so distort the curb out of the circle, as well as to bend the inner lift as a cantilever. (See fig. 6.) We have then two effects to overcome—

(1) The distortion of the curb, cups, &c., out of the circle.

(2) The bending forward of the inner lift as a cantilever, thereby racking all the joints.

(1) Now, in an ordinary way, this tendency to distort is ably resisted by the stiffness of the guide-framing, together with the curb, cups, &c. In this case the guide-framing being done away with to the inner lift, the whole of the distorting forces at the top curb must be met by the stiffness of the top curb (and the adjoining plates) itself. The distorting forces below are resisted the same as ever by the cups and guide-framing. It is evident therefore that the top curb should be made stronger than usual; because, in addition to resisting the dead compressive strains due to the pull of the top sheets, &c., it has to resist the buckling and distorting forces due to the wind pressure, without deriving any assistance from the guide-framing. Good strong rings of plates next to the angle of curb on the top, with an inner angle-iron curb ring is all that is needed, as the top curb is then practically a flat ring-girder, and very stiff. If the top is trussed properly, it is evident that the main rafters, &c., materially assist in preventing distortion. In any case the top curb should be well-gussetted and attached to the vertical stays.

(2) To prevent the inner lift moving bodily forward, and yielding as a cantilever, it would be advisable to introduce diagonal bracing between the vertical stays (as shown by the dotted lines in fig. 6); or otherwise the sheeting—being curved in form would have a tendency to flatten itself between the vertical stays, instead of transmitting the strains properly. This would throw racking strains on the junctions between the vertical stays and curbs. The vertical stays should be strongly secured to the curb and cup as well as rivetted or bolted (all the way up) to the side sheeting.

Assuming that the top curb is a perfectly rigid ring, incapable of deformation, a force applied horizontally would make itself felt equally throughout all the posts on which it stands, and to which it is attached. If these posts are fixed at the base, and there is no web or cross bracing between them, the force has a tendency to break them all off at the bottom, and is then equal to $\frac{1}{2}$ P divided by the number of posts. If they

are not rigidly fixed at the base, but, on the other hand, are free to fall down (being hinged only, as it were, at the bottom end), they would be incapable of resisting any side pressure. They are not, however, merely hinged at the top and bottom ; they are firmly attached to strong rings—in the shape of curbs and cups. The strong rows of plates serve as gussets between these rings and the stays, for they are attached to both. The sheeting also serves to stiffen the structure, and acts, to a certain extent, like the web of a girder.

To sum up, we may safely conclude that—

(7) The inner lift would not rack out of shape when the vertical stays are strong and well attached to strong curbs and sheeting; but as an additional safeguard, diagonal ties may be introduced between the vertical stays, and so relieve the side sheeting from diagonal strain.

MIDDLE AND OUTER LIFTS.

Three-Lift Holders; Two Lifts supported by Guide-Framing.—If the guide-framing reaches to the top of the middle lift, we may take the two outer lifts together as one cylinder, because the one helps the other. It is required to determine whether they are sufficiently rigid and unyielding as to resist the great racking strains which would undoubtedly come upon them ; for on their ability to do so, rests the advisability or not of constructing gasholders with reduced guide-framing.

It is absolutely certain that the outer lifts could not possibly stand suspension from one point on the grip ; and as our examples prove, no pressure of wind or of snow on the inner lift would ever bring about such extreme conditions. [See First Article.] But although they do not exert sufficient force to throw the *whole* weight on one side, yet they have a tendency to do so, and undoubtedly deliver a part of it. The side farthest from the wind has a tendency to fall, when the cup tends to drop from under the grip ; and the side facing the wind has a corresponding tendency to rise. The difference between the lifting force on the one side and on the other is equal to R. The weight, therefore, which the inner lift refuses to support on the left-hand side (or that farthest from the wind) is equal to $\frac{1}{2}$ R ; and the corresponding excess of lifting force on the right-hand side (or that next the wind) is likewise equal to $\frac{1}{2}$ R. So that, as far as the racking or twisting forces are concerned, we may look upon the outer lifts as being acted upon by forces as shown in fig. 11.

The forces $\frac{1}{2}$ R and $\frac{1}{2}$ R. form a couple which must be resisted by the reacting couple F F_1—that is, the reaction of the guide-framing.

$$\tfrac{1}{2}\ \text{R, is equal to } \frac{\text{P}a + \text{S}c}{2b}, \text{ or } 8d^2 + \cdot 33D^2.$$

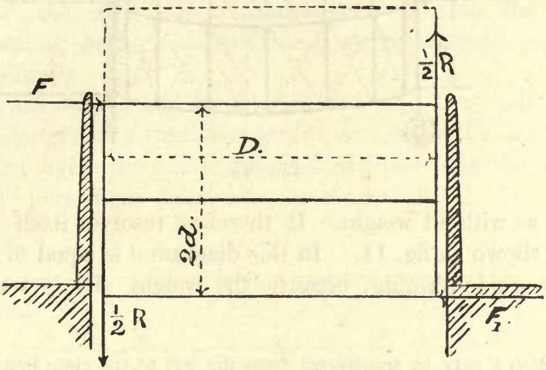

Fig. 11.

In the example of a 200-foot holder $\frac{1}{2}$ R is about 13 tons.

F and F are therefore each equal to

$$\frac{(8d^2 + \cdot 33\text{D}^2) \times \text{D}}{2d} \text{ or } 4Dd + \frac{\cdot 165\ \text{D}^3}{d} = \text{F or F}_1.$$

If only *one* lift out of three is supported by guide-framing, F and F_1 will be increased; thus—

$$\frac{(32d^2 + \cdot 33\text{D}^2) \times \text{D}}{d} \text{ or } 32Dd + \frac{\cdot 33\text{D}^3}{d} = \text{F or F}_1.$$

which for wind is an eightfold, and for snow a twofold increase. $\frac{1}{2}$ R for this latter case is also increased to $32d^2 + \cdot 33D^2$. (See Note G, page 26.)

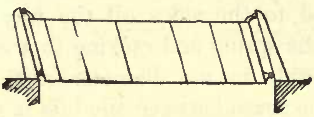

Fig. 12.

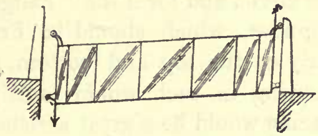

Fig. 13.

There are but two ways in which these outer vessels can yield to the strain, as shown in figs. 12 and 13. The latter (fig. 13) is the more probable, as the external guide-framing *must* be made sufficiently stiff and strong to resist the efforts of the holder to distort, as in fig. 12. The maximum racking strains on the holder, tending to make it

distort, as in fig. 13, are just the same as would be caused by supposing the holder fixed on the one side and loaded on the other to the amount of $\frac{1}{2}$ R; the holder itself

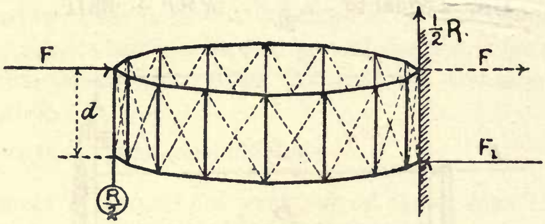

Fig. 14.

being considered as without weight. It therefore resolves itself into a cantilever of peculiar form, as shown in fig. 14. In this diagram *d* is equal to the depth of all the lifts supported by guide-framing, because the weight (R) is transmitted from one to the other.

Note.—The reaction F may be transferred from the left to the right hand side, without altering the magnitude of the maximum strains. It will then hold the body in equilibrium as a simple canti. lever. We only have to observe that the *character* of the strain in the top flange (or cups) would be − instead of +. We must, however, conceive it to be +, as stated below.

It is quite unnecessary to determine the exact strains on *every* bay round the circle; all we want is that of the *maximum*, because each or any bay may in its turn become the most severely strained one, so it would only be confusing the subject to define all the minor strains, which, of course, are embraced by the maximum. (See Note G.)

It is evident at a glance that there is a great racking and twisting at the junction of vertical guide-posts, &c. The hydraulic cups and curbs give much stiffness to it top and bottom; and together with the guide-framing prevent distortion out of the circle, and form the "flanges" of the girder. They are connected by the vertical guides, which should be firmly attached to the sides all the way up, and particularly at the top and bottom, to reduce the spring and racking to a minimum. A little spring in each would multiply considerably in the diameter of the holder. Cross-bracing would be a great assistance; but the space between the lifts is so narrow that it will not admit of its adoption. We are therefore compelled to rely on the side sheets to form the web of the cantilever. Owing to their form, however, they are liable to straighten across corners, as shaded in fig. 13. The vertical posts should be more in number than usual, and intermediate curbs inserted to assist in stiffening the side sheets. The top and bottom row of plates should be extra strong, and the vertical posts firmly attached to them.

These outer lifts, of course, have their own wind pressure to resist, in addition to the above strains; but it is comparatively slight in its effect, as it is all transmitted to the external guide-framing, without tilting the holder, as the guide-framing must be strong enough to resist the overturning force by itself, relying upon the holder only for assistance in resisting distortion out of circular shape (in plan). The nature of the strains due to the load $\frac{1}{2}$ R is compression in both the top and bottom rings; the guide-framing being made sufficiently strong to resist distortion out of the circular shape horizontally.

Approximately, the strains may be determined thus: Take half the circumference of the holder as the length of a cantilever girder, and make the depth equal to that of the outer lifts. Then divide the girder into as many panels as there are vertical stays or guide-posts, and join them diagonally, as shown in fig. 15. Then if $\frac{1}{4}$ R be

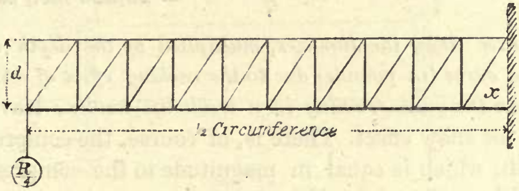

FIG. 15.

applied at the end, the same strain will be induced in the most severely strained bay x as would be produced by distributing the exact weight on each post. (See Note G.)

In a cantilever, the strain on either top or bottom flange will be equal to

$$\frac{\text{load} \times \text{length}}{\text{depth.}}$$

In this case, therefore—

$$\text{Load} = \text{for wind and snow together } \frac{8d^2 + \cdot 33D^2}{2} = \tfrac{1}{4}\,\text{R}.$$

$$\text{or } 4d^2 + \cdot 165\,D^2.$$

$$\text{Length of cantilever} = \frac{D \times 11}{7}$$

Depth of cantilever = $2d$, or depth of two lifts.

Collecting these results, we have: Maximum strain on the bottom curb (*compression* due to racking)—

$$\frac{(4d^2 + \cdot 165\,D^2) \times \cdot 11D}{7 \times 2d} \text{ or roughly } \frac{3d^2 + \cdot 14\,D^3}{}$$

where D = diameter of one lift; d = depth of one lift.

Applying this to a three-lift gasholder, 200 feet in diameter by 45 feet deep (each lift), we have—

$$\frac{(3 \times 45^2 \times 200) + (\cdot 14 \times 200^3)}{45 \times 2240} = \text{about 23 tons.}$$

If this were the *only* strain on the bottom curb, it would require at least 6 square inches sectional area to withstand it; but there is the *bending* strain due to the slightly curved form, as well as other structural strains, and that due to wind pressure on the two lower lifts. The effect of this latter is similar to that shown by fig. 9. It is comparatively simple, however, to determine the allowance for these. The 6 inches is what is required *extra*, due to the new form of holder. (See Note H, page 33.)

If wind only be considered (omitting snow), we should have—

$$\frac{4d^2 \times 11\,D}{14d}, \text{ or } \frac{22\,Dd}{7}, \text{ or } \frac{200 \times 45 \times 22}{7} = 28{,}286 \text{ lbs., say } 12\tfrac{1}{2} \text{ tons,}$$

or approximately, *three times the diameter, multiplied by the depth of one lift = the compression on the bottom curbs (in pounds) due to the racking effect of wind pressure, when the inner lift only is above the guide-framing in a treble-lift holder;* leaving therefore in this case about $10\frac{1}{2}$ tons for snow effect. There is, of course, the compression in cups at the top of the middle lift, which is equal in magnitude to the compression on the bottom curb. These should be stiffened up, if necessary, to suit.

The diagonal or cross strain on the side sheeting in the most severely strained bay is equal to $\frac{1}{4}$ R, multiplied by the diagonal distance across from corner to corner of the bay in one lift, and divided by its depth (= in this case about 7 tons). This is where the greatest yielding to deflection will occur. Indeed, it will be impossible to avoid a little deflection in the outer lifts, in which case the inner lift falls with them, and continues to do so until the outer lift is able to resist the load. But when properly constructed, we may conclude that—

(8) ***Gasholders can be constructed safely with the inner lift unsupported by external guide-framing after it has cupped, provided the guide-framing is carried to the height of the two outer lifts.***

Three-Lift Holders; One Lift supported by Guide-Framing.—In this case, when two lifts tower above the guide-framing, the strains are considerably increased. The strain on the *inner* lift remains as before; but the *middle* lift has the former strains augmented by the absence of support from the guide-framing, and the consequent increase of strain from wind pressure, tending to overturn it. The force R does not now affect the middle lift. R must, therefore, be resisted entirely by the outer lift, which alone is held level and firm by the guide-framing.

The side pressure tending to rack the joints, as shown in fig. 16, is equal to 16 Dd, where $d =$ the sum of the depths of the inner and middle lifts, and is applied on a level with the top of the middle lift (see fig. 16). This illustration also shows the manner in which the middle lift *tends* to distort when the other two are doing their duty. The greatest stress, however, comes upon the outer lift, because it not only has to transmit all the transverse strain to the guide-framing through the roller carriages, but also to resist the greatly increased strains due to the tendency of the two upper lifts to tilt.

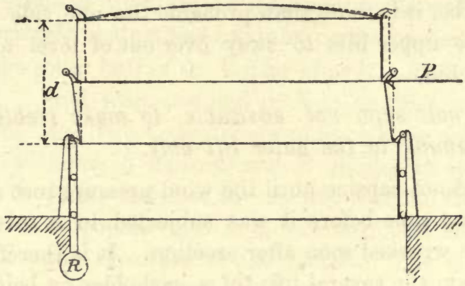

FIG. 16.

Treating the sides of the outer lift as a developed cantilever, we have for the load due to—

Wind and snow combined

$$\frac{32d^2 + \cdot33\text{D}^2}{2} = 16d^2 + \cdot165\ \text{D}^2.$$

$$\text{Length of cantilever} = \frac{\text{D} \times 11}{7}, \text{ as before.}$$

$$\text{Depth of cantilever} = d.$$

Collecting, we have for maximum strain due to wind and snow—

$$\frac{(16d^2 + \cdot165\ \text{D}^2) \times 11\ \text{D}}{7d}, \text{ or roughly}$$

$$\frac{25d^2\ \text{D} + \cdot26\ \text{D}^3}{d} = \text{compression on curb.}$$

For the same size gasholder as before, we have—

$$\frac{(25 \times 45^2 \times 200) + (\cdot26 \times 200^3)}{45} = \text{fully 121 tons.}$$

If we take wind force only, the compression on the bottom curb is approximately 25 *times the diameter, multiplied by the depth of one lift, in a three-lift holder with two lifts*

towering above the guide-framing, which, in this case, is $25 \times 200 \times 45 = 225{,}000$ lbs., or fully 100 tons, which would require an extra sectional area in bottom curb of (say) 25 square inches to resist *wind* alone. We see from this that the strains in the bell itself due to wind are just *eight* times greater when two lifts are free than when only one lift is free. Then this is depending upon the side sheeting to act as the web plate of a girder; but the diagonal strains due to the increased load would be so great (viz., about 38 tons in the most severely strained bay, or, $\frac{1}{2}$ R, multiplied by the diagonal distance across from corner to corner of one bay in the outer lift, and divided by its depth) that, together with the great racking strains on the junctions between the vertical guides and curbs, it is more than probable the one side would deflect or drop so much as to cause the upper lifts to sway over out of level to a dangerous extent. We may therefore conclude—

(9) *That it is not safe, nor advisable, to make treble-lift gasholders with guide-framing to the outer lift only.*

Of course, it would not capsize until the wind pressure rose sufficiently high to do it. It might exist a long time before it was subjected to a severe gale; but, on the other hand, it might be wrecked soon after erection. It is therefore unwise to risk it. Neither can we look upon the several lifts of a gasholder as being parts of one continuous cantilever, without a break. The junction between one lift and another cannot be made so perfectly stiff as to answer such conditions. If, in addition to cup rollers, outside rollers be fixed to work up the sides of the inner lift, the greatest telescopic grip they can have is but 2 or 3 feet, which is insufficient to constitute a continuous cantilever. If it *were* a continuous cylinder, without any break from top to bottom, the racking strains would be considerably less.

Note D.

It may not be out of place to make a few remarks on the assumed positions of the centres of force, &c.

The centre of gravity of the middle lift of a gasholder is exactly in the centre of its depth—that is to say, midway between the cups. The centre of gravity of the outer lift is slightly higher than half its depth, because the grip is a little heavier than the bottom curb, and so raises the centre of gravity a little. The centre of gravity of the inner lift is more difficult to determine, because it varies with different sized holders, trussing or not trussing, thickness of top sheets, &c. But for all practical purposes, we may reckon it to be one-quarter of the depth down from the top curb.

Of course, it can be worked out exactly; but it is somewhat tedious, and is quite unnecessary.

The centre of buoyancy is taken as the centre of the volume—the same as in a floating ship, it is the centre of the volume of water displaced.

The centre of wind pressure is undoubtedly the centre of gravity of the *area* acted upon; not the centre of gravity of the whole mass of the structure, which has nothing to do with its centre of action.

NOTE E.

It is perhaps advisable to illustrate the statement made with regard to gas pressure pushing the holder forwards against the columns on the opposite side to the wind, and dragging, as it were, the other half of the holder after it. Take a box filled with water, and place one end of it in another one, as shown in fig. 17; the two boxes being able to slide freely in one another—A being a fixture, and B sliding in it, having a water-tight joint, and free to slip out without friction. Now, if water be poured into A, it will be found that B will glide out in the direction of the arrow. The reason is this: If both boxes be equally full of water, the pressure on both sides of C is *equal* and opposite, and therefore balanced, and has an equal tendency to move in either direction; so that the effect of the pressure is *nil*. But on the side D, we have a pressure *unbalanced*. Therefore it will take full effect in moving the box onwards. It is the pressure of water in B on the side D which moves the box—not the pressure in A thrusting it forward, as it would if B were empty. If the box A were empty, of course the pressure of water in B at the opposite ends of the box would cause a tension in the sides, and pull in equal amount in opposite directions; but as soon as the pressure on C is relieved by filling A, it is no longer able to resist the pull of D. Applying this to a gasholder: Water in A is the wind; B is the holder full of gas. The wind partly neutralizes the pressure on C, leaving the pressure on D unbalanced, and free to move the structure.

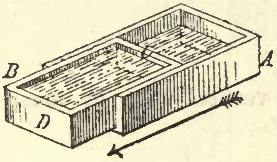

FIG. 17.

NOTE F.

(1) The gas pressure can be found by the following formula:—

$$\frac{Ddp}{1425\ N} = g$$

D and d = diameter and depth of inner lift respectively.

p = pressure of gas per square foot, in pounds.

N = number of vertical stays.

g = the pressure acting at top of *each* vertical stay, in tons.

(2) The wind pressure is more difficult to dispose of, because it is most intense on the part of holder normal to the direction of the wind, and gradually decreases as it comes round the curve to the right and left. But the following formula will enable us to distribute it according to its value over each of the vertical stays on the wind side :—

$$\frac{DdQ}{280\ Y} = p, \text{ where}$$

D and d = as before.

Q = the length of the ordinate opposite the post for which p is sought.

Y = the sum of all the ordinates opposite the vertical stays Q, Q_1, Q_2, &c., measured to the diameter perpendicular to the direction of the wind.

p = the thrust, in tons, against the top of any particular vertical stay, (approximately).

(3) The pull of the top sheets inwards can be found thus—

$$\frac{Df\,(a^2 + b^2)}{2850\ Nb} = \text{the pull supposed to act at the top of each vertical stay, in tons.}$$

D = diameter of holder, in feet.

f = the *effective* pressure of the gas per square foot, in pounds.

a = the half diameter of the holder, in feet.

b = the rise of crown, in feet.

N = the number of vertical stays.

Note G.

A very good illustration of the effect of the one-sided lifting force on the lower lifts of a gasholder (when the upper one is free and acted upon by the tilting forces) may be got from a wide-fronted but short drawer. If we attempt to open it by pulling on

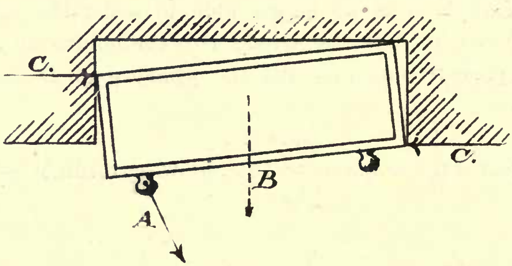

Fig. 18.

one side, as shown in fig. 18 by arrow A, we find a great deal more resistance than if we pull fair in the centre, as at B. It has a tendency to jam, due to the reactions C C.

If this diagram be turned upside down, we have an exact illustration of the gasholder under similar conditions.

The distribution of the load, and its effect on the various lifts may be made very clear by considering the following diagrams :—

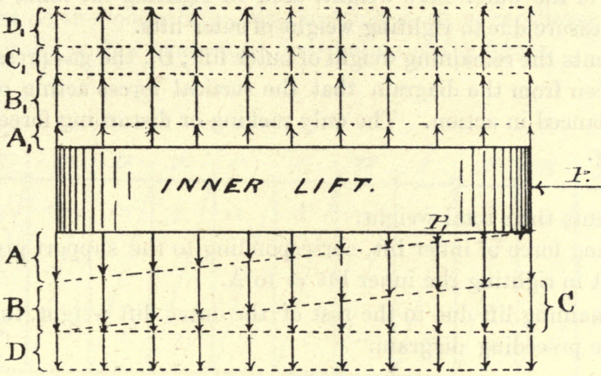

FIG. 19*a*.

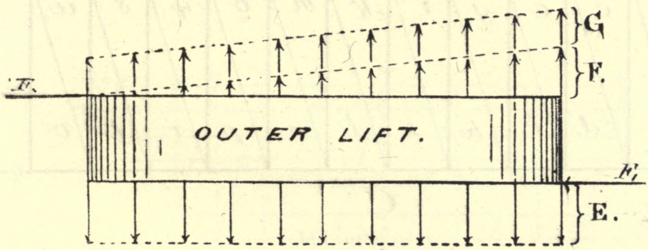

FIG. 19*b*.

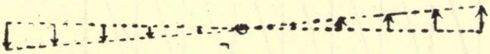

FIG. 19*c*.

The upward forces are shown by the arrows distributed on the top of the lifts ; and

the downward forces by the arrows on the under side of the lifts. The length of the arrows signify the intensity of the forces.

Inner lift—

A is the weight of the snow ; A_1, the corresponding lifting pressure of gas.

B is the weight of inner lift ; B_1, the corresponding pressure of gas.

C is part of the outer lift's weight, used in righting the inner lift ; C_1, the gas pressure due to righting weight of outer lifts.

D represents the remaining weight of outer lift ; D_1, the gas pressure due to this.

It will be seen from the diagram that the vertical forces acting on the inner lift are even and balanced in action. The only racking or disturbing force being P, which acts horizontally.

Outer lifts—

E represents their total weight.

F the lifting force of inner lift, corresponding to the support given by the outer lift in righting the inner lift = to A.

G the remaining lift due to the rest of the outer lift weight, the same as D in the preceding diagram.

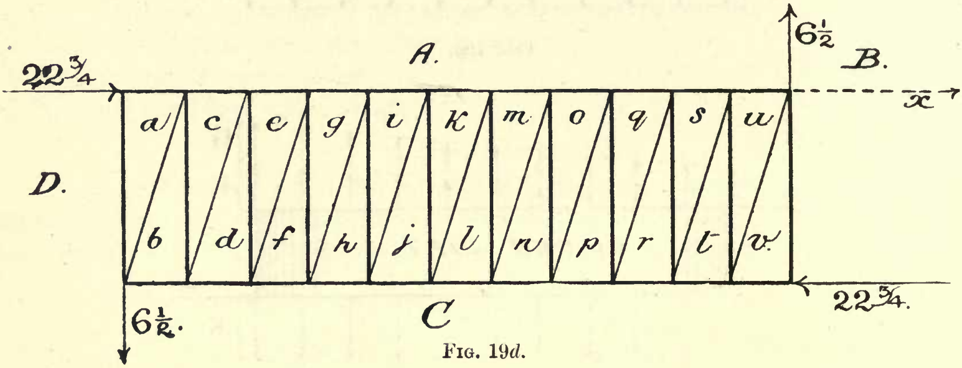

FIG. 19*d*.

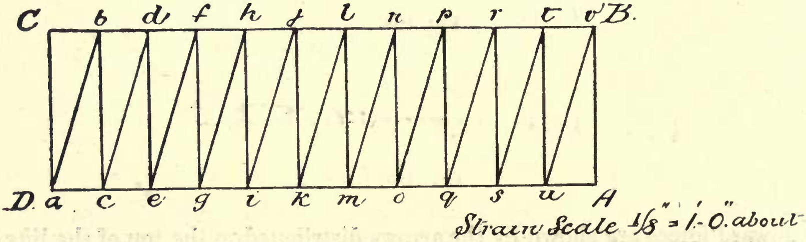

FIG. 19*e*.

This clearly shows the one-sided lift of the forces on the outer lifts; the total weight of the outer lifts E being = the total lift G + F.

Balancing up the forces on the outer lifts, therefore, we have the substituted diagram, fig. 19*c*. (p. 27), which shows the resultant *twist*, due to the depression on one side and the lift on the other.

We may prove the correctness of the simple method adopted in the articles for finding the strains on the outer lifts—viz., treating it as a cantilever—by comparing the results graphically with a more exact distribution of the forces.

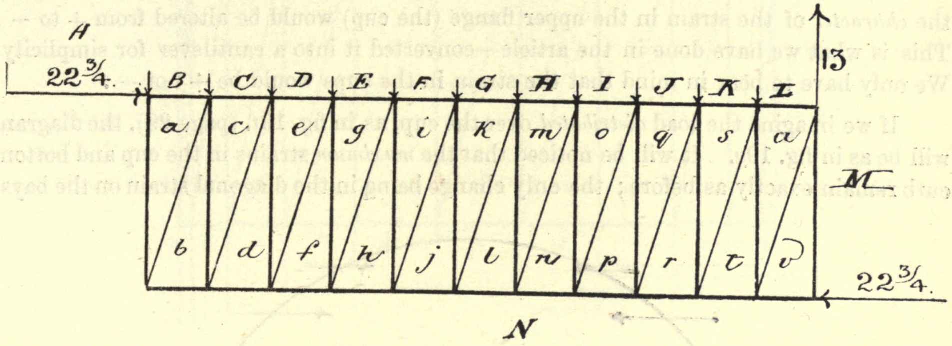

Fig. 19*f*.

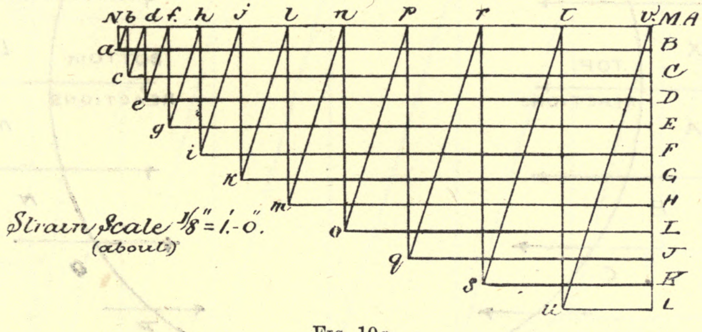

Fig. 19*g*.

Fig. 19*d*. is the half circumference of holder, developed as directed in the article, and acted upon by the lifting and depressing forces with their reactions. Fig. 19*e*. is

the diagram of strains, drawn to scale, by Clerk Maxwell's method with Bow's lettering.

It may be explained briefly that the lines in the diagram represent the strains in those parts to which they are parallel in the frame. The lettering is simply lettering the *spaces* on both *sides* of a line in the frame, instead of at each end. Then the strain in the diagram is always denoted by the same letters as the line it refers to in the frame. For example, the strain in the part of the bottom curb represented by Cv in the frame, is equal to the length of the line Cv in the reciprocal diagram.

Now, it will be seen that, if the reaction AD (fig. 19*d.*) be transferred to x (as dotted), the maximum strains in the frame will not be altered. The only difference is the *character* of the strain in the upper flange (the cup) would be altered from + to −. This is what we have done in the article—converted it into a cantilever for simplicity. We only have to bear in mind that the strain in the cups would be + not −.

If we imagine the load *distributed* over the cup, as in fig. 19*f.* (page 29), the diagram will be as in fig. 19*g*. It will be noticed that the *maximum* strains in the cup and bottom curb remain exactly as before; the only change being in the diagonal strain on the bays,

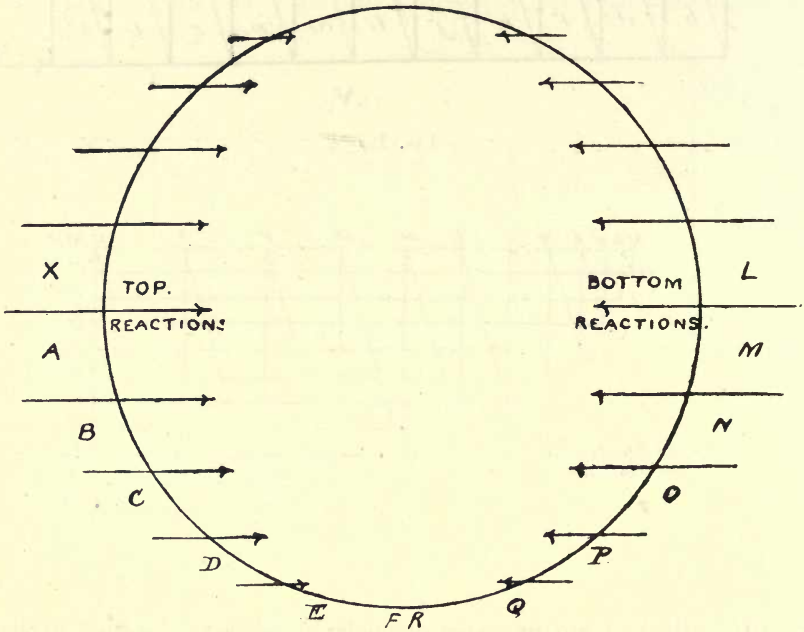

FIG. 19*h*.

which is *doubled* in the bay having maximum strain. This is approximately correct, and we have therefore allowed for it in the rule for diagonal strain given in the article.

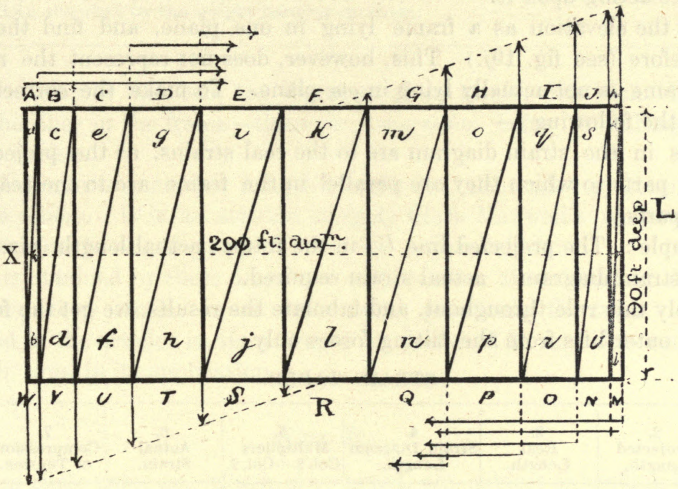

FIG. 19*i*.

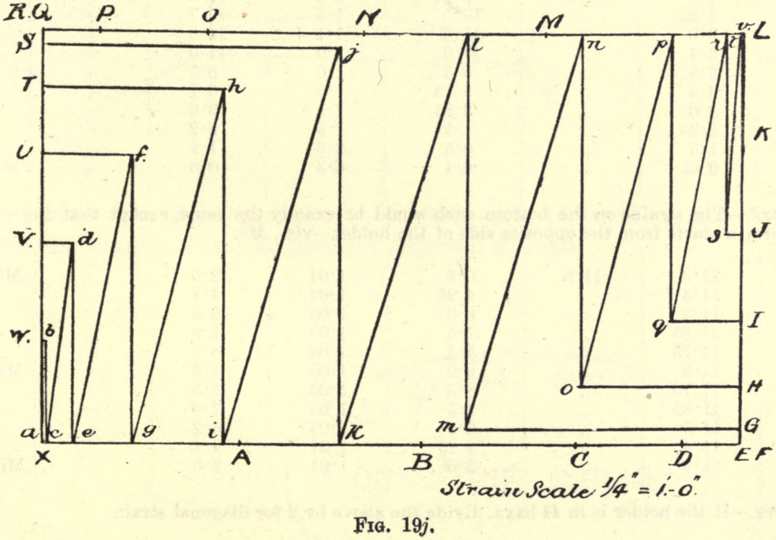

FIG. 19*j*.

We will now give a still more exact demonstration; and instead of supposing the forces acting in isolated positions, we will distribute them over the holder framing as shown in figs. 19*h.* and 19*i.* which are a plan and elevation of the framework, together with the forces acting upon it.

We treat the elevation as a frame lying in one plane, and find the reciprocal diagram as before (see fig. 19*j.*) This, however, does not represent the real strains, because the frame is not actually lying in *one* plane. To make the corrections, therefore, observe the following :—

The lines in the strain diagram are to the real strains, as the projected lengths of the parts to which they are parallel in the frame are to the real lengths of those parts.

For example : The projected line *Uf* in the frame : actual length (viz., Rl) : : *Uf* in the strain diagram : actual strain required.

If we apply this rule throughout, and tabulate the results, we get the following for strains in the outer lifts from the tilting forces only :—

STRAIN TABLE.

1. Line in Frame.	2. Projected Length.	3. Real Length.	4. Strain Diagram Length.	5. Multipliers Col. 3 ÷ Col. 2.	6. Actual Strain.	7. Compression or Tension.	8. Remarks.
CUPS.							
A *a*	0·55	3·5	3·75	6·3	23·7	+	Maximum.
B *c*	1·5	,,	7·75	2·3	17·9	+	
C *e*	2·25	,,	10·5	1·5	15·7	+	
D *g*	3·0	,,	11·5	1·1	12·6	+	
E *i*	3·4	,,	11·0	1·0	11·0	+	
F *k*	3·5	,,	8·5	1·0	8·5	+	
G *m*	3·4	,,	5·75	1·0	5·7	+	
H *o*	3·0	,,	3·25	1·1	3·6	+	
I *q*	2·25	,,	1·5	1·5	2·2	+	
J *s*	1·5	,,	0·5	2·3	1·1	+	
K *u*	0·55	,,	0·1	6·3	0·6	+	Minimum.

NOTE.—The strains on the bottom curb would be exactly the same, except that the maximum strain starts from the opposite side of the holder—viz., *Mv*.

DIAGONALS.							
a b	11·3	11·8	0·2	1·04	2·0	–	Minimum.
c d	11·4	,,	4·25	1·04	4·1	–	
e f	11·5	,,	6·0	1·03	6·2	–	
g h	11·65	,,	7·5	1·03	7·3	–	
i j	11·75	,,	8·5	1·00	8·5	–	
k l	11·8	,,	9·0	1·00	9·0	–	Maximum.
m n	11·75	,,	8·5	1·00	8·5	–	
o p	11·65	,,	7·5	1·03	7·3	–	
q r	11·5	,,	6·0	1·03	6·2	–	
s t	11·4	,,	4·25	1·04	4·1	–	
u v	11·3	,,	2·0	1·04	2·0	–	Minimum.

NOTE.—If the holder is in 44 bays, divide the above by 2 for diagonal strain.

VERTICALS.							
$j\,k$	11·25	11·25	$8\frac{1}{4}$	1	$8\frac{1}{4}$	+	Maximum.
$t\,u$	11·25	11·25	2	1	2	+	Minimum.

NOTE.—All the verticals are not given here; but they are not of much account, as the + strain is more than absorbed by the weight hanging on them.

In all these graphic methods, the character of the strains has been shown by the thickness of the lines in the frame—those in *compression* being *thick* lines; the *thin* ones denoting *tension*.

The last diagram is somewhat tedious to work out, although very simple and more exact than the others. It is an attempt to apply Clerk Maxwell's reciprocal diagram method to structures having their parts in several unparallel planes.

The results obtained by these diagrams only confirm the rules laid down in the articles; the *maximum* strains in all cases being practically the same. The simple method adopted in the articles is, therefore, to be preferred to any elaborate treatment involving much time in its application.

NOTE H.

The bottom curb, cups, &c., which are curved, are subject to bending between the columns or points of support. They should therefore be stiff, to avoid springing as

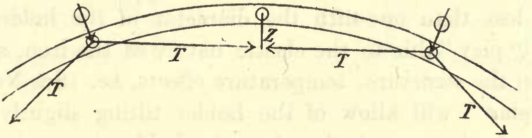

FIG. 20.

much as possible. The bending moment in the curb is equal to the thrust T multiplied by the leverage Z (see exaggerated diagram, fig. 20).

THIRD ARTICLE.

STRENGTH AND RIGIDITY OF GUIDE-FRAMING OF VARIOUS KINDS.

We have now to consider whether it is possible to comply with the second condition necessary for gasholders with reduced guide-framing—viz., *that the guide-framing must be perfectly stable, and at all times preserve the level working of the holder.*

The stability of the framing depends entirely upon its ability to resist the strains coming upon it. If it be strong enough to do this, there will be no doubt about its stability.

Then, as regards the level working of the holder. There can be no trouble in this respect, providing the distance from tier to tier of rollers, or the depth of each lift, is sufficient—*i.e.*, not less than one-fifth the diameter of the holder. There will undoubtedly be a little "play" due to the elastic nature of the iron, and the multiplicity of parts and joints in the structure, temperature effects, &c. (See Note I, on elasticity, page 53.) This "play" will allow of the holder tilting slightly under heavy wind pressure; but it can be but very little when the holder is constructed to resist the strains pointed out in the previous articles.

We have, then, to determine the strains on the various parts of the guide-framing before we can answer for its stability. But before doing so, it will be well to distinguish between the different kinds of guide-framing in use, as the method of determining the strains necessarily varies somewhat according to the design.

The most modern is what may be termed the cantilever type of guide-framing, because the whole guide-frame forms one vertical cantilever, and is, in fact, a hollow stiffened cylinder, lightened out in the shell (fig. 21). It is stiffened by an internal cylinder, concentric, and in contact with it—viz., the holder or bell. The outer cylinder alone is attached at the base; the inner one fitting freely within it, and at liberty to rise and fall. The guide-framing has, of course, a tendency to buckle, owing to its

huge dimensions; but it is preserved in cylindrical form, partly by the stiffness of the rings of cups, curbs, and girders, and partly by the support rendered vertically by its attachment at the base, and the long deep stiffeners in the form of standards. That is, the cylindrical form cannot be distorted to any considerable degree without breaking the standards transversely, or by rooting up the foundation bolts. This alone proves the great value of the external guide-framing. The lifts which project above the top of the guide-framing, when the latter is reduced in height, are subject to bending as a cantilever, and induce racking and bending strains on the framing below; but they do not save the guide-framing any strain—they only get what would otherwise be taken by the *upper* part of the guide-framing done away with. The standards are strained just as much in the lower part as they would be if carried to the full height, as usual. As a cantilever, the strain on half of the columns is crushing; the other half being tensile or lifting. The strains are transmitted from one column to the other by means

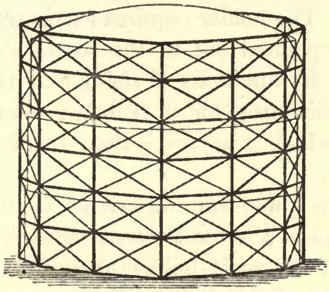

Fig. 21.

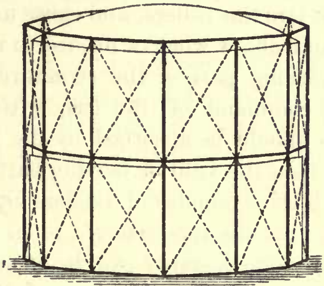

Fig. 22.

of the diagonal bracing and girders, which take the strains like lattice bracing in a girder. (The girders are the *struts*, and the diagonals the *ties*.) The magnitude of these strains is determined later on.

We have said enough to distinguish this form of gasholder from the old-fashioned type (see fig. 22), whose guide-framing consisted practically of a series of independent posts, connected together by horizontal girders and perhaps light diagonal ties—quite inadequate, however, to form it into a cylinder capable of standing much strain as such. This latter type of holder is more like a ring of independent cantilevers than one huge one. It has its good points, however. Owing to the heavy, strong, and widespread based standards found necessary, it is better able to preserve rigid guiding for the free working of the holder, than the light springy framing which depends upon the holder to a much greater extent for its preservation of form and lateral

stiffness. The cantilever cylinder type, it is true, possesses the advantage of requiring less material to get equal strength, and is more scientifically correct; but it is more costly and difficult to erect, weight for weight, owing to the nice adjustment required of all the parts, to get them to take their proper share of strain and to fit properly. Again there are more separate pieces to deal with, and joints to make, than in the old form. It is for this reason probably, together with that of appearance, that we often find engineers striking a mean, as it were, between the two extremes—a fine example of which, designed by a Past-President of The Gas Institute (Mr. Gandon) may be seen at the gas-works, Lower Sydenham. The best examples of the advanced cantilever type are Mr. Livesey's gasholders at Old Kent Road and East Greenwich. Mr. Charles Hunt's new holders at Birmingham are also fine specimens of this class, but of slightly heavier construction.

It is doubtful whether it is advisable to make the holder help the guide-framing much, especially in the recently introduced shortened guide-framing type of holder, as it must jam the rollers, and cause uneasy working. The holder requires extra strength over and above what is needed to meet the strains pointed out in the second article. The working part of the structure should perform its functions of rising and falling to the command of the gas, without undue restrictions; for it is better that the strains should be absorbed by the guide-framing—which is at rest—than thrown too much upon the vital or moving part of the structure,

All the examples of holders cited above have the guide-framing carried to the full height; but the type referred to in the last paragraph is the most recent construction, and only one instance can be mentioned—viz., Mr. Livesey's holder at Rotherhithe, which has the guide-framing reaching to the height of the two outer lifts only; the inner lift being entirely above the framing when the holder is fully inflated. It is with this new type of holder we have been dealing exclusively in the previous articles, because experience has already determined the proper proportions and strength for the old style of gasholders. There is, therefore, little necessity to treat of them; but as the reduced guide-framing type of gasholder is a serious departure from all previous construction, it behoves us to be cautious and look at it from all points, both theoretically and practically, before recommending it for adoption as a general thing.

It has been determined in previous articles to what extent it is admissible to diminish the height of the guide-framing from considerations which affect the strength of the bell, &c. It will not therefore be needful to refer to the suggested abolition of guide-framing altogether, or of shortening it to within a few feet of the ground; both of these suggestions being regarded as outside the province of practical engineering. (See Note J, page 54.)

STRAINS IN GUIDE-FRAMING.

The following is the course to be adopted in finding the strains :—

I.—Determine the external forces acting upon the guide-frame, both in magnitude, direction, and distribution.

II.—The two-fold effect these forces have on the structure.

III.—The manner in which the structure resists them—defining the strain on each of the members composing it.

I. As regards the external forces, they may be summed up as (1) wind, (2) snow, and (3) wedge-action of holder. All three forces are distributed over the holder; but they are transmitted to the guide-framing through the roller carriages; these being the only points of contact between the inner and outer cylinders—viz., the bell and the guide-frame.

(1) The magnitude of wind pressure has been stated in previous articles. The total force of wind is equal to $16Dd$ where $D =$ the diameter, and $d =$ the total depth of holder, in feet. This force is given out at two or more circles up the guide-frame; but we may, for convenience, determine the resultant force, which must be applied at the *top* of the guide-frame to give the same strain as would be derived from the actual forces applied at intervals.

Referring to fig. 23 (on next page), the resultant force F, in pounds, as far as wind pressure affects the holder, is equal to—

$$\frac{16\,Dd \times d}{2\,H} \text{ or } \frac{8\,Dd^2}{H}$$

NOTE.—The guide frame itself is subject to wind pressure; but this can be neglected, as $16\,Dd$ covers it.

(2) The pressure of snow (S), as already explained, is equal to D^2. This force induces an upsetting couple, whose effect can be measured by $S \times \frac{D}{3}$ (fig. 23), and which, divided by H, will give the horizontal effect at F, or $\frac{D^3}{3\,H}$, which must be added to the foregoing wind effect to give the total resultant force F, in pounds.

(3) Unless the lifts are less in depth than one-fifth of the diameter, there can be no trouble arise from wedge-action, in a properly-designed holder; and it can therefore be disregarded.

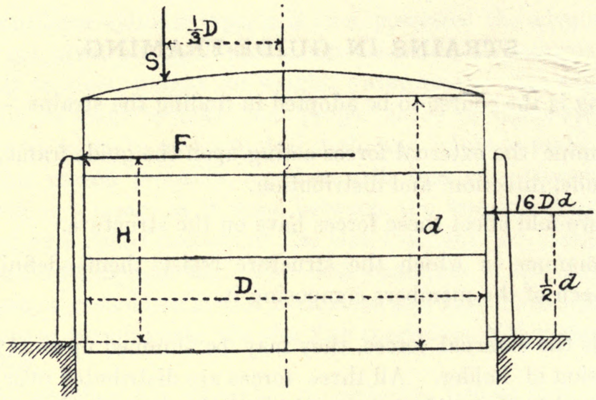

FIG. 23.

We have, then, a total capsizing force acting horizontally at the summit of the guide-framing equal to—

$$\frac{8\ Dd^2}{H} + \frac{D^3}{3\ H} = F.$$

(See Note J for thrust on bottom rollers, &c.)

II.—We have now to define the two-fold effect which these forces have upon the huge cantilever.

(1) They tend, in the first place, to break it off at the base; and to do so, half of the columns must be *crushed vertically downwards*, and the other half must be *lifted vertically upwards*—*i.e.*, if the framing be a true cantilever, half of the columns supply the place

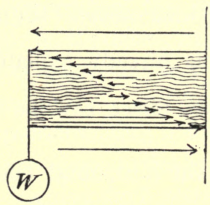

FIG. 24.

of the compressed fibres in a beam, and the others the tensile fibres (see fig. 24). But in order to resist the stress in this way, the connecting bracing between the columns

must be sufficiently strong to transmit the strain from one column to the other all round the circle. So that we not only have to provide for the *dead compressive and tensile strains in the columns,* but likewise for *the strains in the struts and ties forming the bracing,* and which bind it together to form one cylinder. We shall endeavour to show, in a simple manner, how to determine and provide for both of the above.

(2) But in addition to this capsizing tendency, the cantilever, being of such huge dimensions, and of comparatively frail character, is subject—like all structures of the kind—to *buckling;* and this brings us to the second effect of the forces.

This buckling may be looked upon correctly as a tendency to distort out of the circle horizontally, and is due principally to the unequal distribution and unbalanced state of the forces as shown in figs. 9 and 10. (See Second Article.) As already stated, the gasholder bell, fitting within the cantilever frame, renders assistance in resisting this distortion by means of its strong rings in the form of cups, curbs, &c. It is more a matter of judgment and experience, than of calculation, as to the value of the assistance they render. (See Note K, page 55.)

In the case of the top curb, when made extra strong and properly designed—being virtually a ring plate girder—it could be depended upon for preserving the guide framing in its circular form at the top end. The standard then becomes a beam supported at each end and loaded opposite the cups. When, however, the top curb has only been designed of just sufficient strength to resist the dead compressive strains due to the pull of the top sheets only, it cannot be relied on for much support. The standard then becomes a cantilever or beam fixed at one end—viz., the base ; or it may receive partial support at the top end, and so be in a condition between the two. The same thing occurs when the guide-framing does not reach the full height, as in that we are dealing with more particularly in these articles.

The bottom curb is unable to distort out of the circle, owing to the rigid wall of the tank ; and this exercises an influence over the lower part of the holder in preventing distortion. The cups, however, owing to their being very narrow rings compared with their diameter, cannot be relied upon for any substantial support. What, therefore, they refuse to render must be taken by the guide-framing itself. The value of the resistance to distortion rendered by the cups, necessarily varies according to the strength and number of them, and also as to whether they are required to resist racking strains from unsupported lifts. But as general, easily-applied rules, the following may be relied upon.

III.—The *bending moment* (due to distorting forces) on one standard of the guide-framing—when the guide-frame is so thoroughly braced as to form it into a complete

cylindrical cantilever, and is of the *full height* of the gasholder (as in fig. 37 page 59), the top curb also being sufficiently strong to resist the distorting force at the top—may be found thus :

$$\frac{B\,H^2}{270} = M,$$

Where B = the distance, centre to centre of the columns, or *one bay* (in feet),
H = the total height of the holder (in feet),
M = the bending moment required (in inch-tons).

If this be divided by the breadth of the standard—*i.e.*, the distance from front to back—it will give the total strain on either flange,

or $\frac{B\,H^2}{270\,K}$ = strain on one flange in *tons*, where K = the width of standard in *inches*. (See examples for more definite determination of K.)

or $\frac{B\,H^2}{270\,Ks}$ = strain per square inch on iron, where *s* equals the sectional area of one flange in square inches.

NOTE.—Working on the basis of a 40 lbs. wind pressure, Mr. B. Baker takes the effective distorting force on a gasholder (as here described) as equal to 14 lbs. pressure per square foot, distributed over a surface equal to about three-fourths of the total depth of the holder, multiplied by the distance between two columns. In our case we are only providing for a wind pressure of 30 lbs. The pressure would therefore be about 10 lbs. per square foot, if reduced in proportion. This total presssure he considers as distributed over a length of standard equal to 11-16ths of its height, or (say) three-fourths of the total depth of the gasholder. We cannot do better than follow this rule, as it accords very closely with the best practice; and it is upon this, therefore, that the above formulæ are founded.

When, however, the top curb cannot be relied on for any external support, it is obvious the strains on the standards are considerably increased. The three formulæ will then be as follows :—

$$\frac{B\,H^2}{180};\quad \frac{B\,H^2}{180\,K};\quad \frac{B\,H^2}{180\,Ks},\ \text{respectively.}$$

NOTE.—Although the top curb and cups cannot be relied upon for perfect support, yet, before the gasholder guide-frame could be destroyed, they would offer considerable resistance. This has been considered in fixing the above formulæ.

But it is not so much with gasholders having the guide-framing carried to the full height that we have to do, as with those of the reduced guide-framing type. Here, it is certain, no support can be rendered to the framing by the top curb, as it is out of reach. We have, then, to rely upon (1) such cups as are below the summit of the guide-frame; (2) the inherent stiffness of the guide-framing itself due to the system of

cross-bracing; and (3) the resistance offered by each standard (acting as a vertical stiffener) to bending backwards as an independent cantilever. The top curb and those cups which tower above the top of the guide-framing, *must* be made sufficiently strong to resist the distorting force coming upon them, as they cannot receive any direct help from the framing. We know that the cups are incapable of standing much strain in this way; so we may consider this as almost fatal to lowering the guide-framing very much below one lift. If the guide frame were reduced to a few feet from the ground, practically the whole of the distortion would come upon the holder, which it could not resist, not even if we disregard the other severe strains that would come upon it (as pointed out in the previous articles) consequent on such construction.

If the guide-framing be shortened by the depth of one lift (as in figs. 35 and 36 page 58), the strain on the standard may be found approximately by the following rule:—

$$\frac{B\,H^2}{130} = \text{bending moment at } \textit{foot} \text{ of standard.}$$

The other two formulæ will read $\frac{B\,H^2}{130\,K}$ and $\frac{B\,H^2}{130\,Ks}$ respectively.

If it be required to determine the moment of resistance of a simple cast-iron column to bending—

$$\frac{A\,d_1}{1 \cdot 6} = R,$$

Where A = sectional area of column, in square inches.

d_1 = diameter of column (*mean*), in inches.

R = moment of resistance of cross section, in inch-tons (*safe*).

This is approximately true (see Note L, page 56) when the safe resistance of the material is taken at $2\frac{1}{2}$ tons per square inch, as a maximum strain.

When we know the bending moment on a column, as determined by the above rules, we can, of course, find either the *thickness* or *diameter*, or *sectional area* of the column when we settle on one of them.

Suppose we fix the diameter of column d_1, then

$$\frac{B\,H^2}{C} \times \frac{1 \cdot 6}{d_1} = A\text{; or shortly } \frac{1 \cdot 6\,BH^2}{C\,d_1} = A$$

where C is the constant 270, 180, or 130 according as to which of the three forms of construction is adopted.

We can determine the thickness when we know the sectional area required for the

given diameter, because in a thin column we may, for all practical purposes, take the thickness as—

$$\frac{A}{3 \cdot 14 \times d_1} = t.$$

$$\text{Hence, } t = \frac{1 \cdot 6 \, BH^2}{3 \cdot 14 \times d^2_1 C}, \text{ or approximately } = \frac{BH^2}{2 \, Cd^2_1}$$

Which is as simple and handy a rule as could be desired.

If the thickness be given and the diameter is sought—

$$d_1 = \sqrt{\frac{BH^2}{2 \, Ct}}$$

These rules would apply to the column at a point half-way up the height of the gasholder, if the column were merely like a beam resting freely on supports at each end; but as the column or standard resembles a beam *fixed* at one end—viz., the base—and freely or partly supported at the other, the greatest bending moment, due to the distributed distorting forces, is at the base. We may therefore apply the rules for determining the thickness of the shaft just above the base. But, in addition to the thickness thus found, the sectional area must be augmented, in order to provide for the *direct vertical stress* upon the column due to its own weight and that of the allied framing, and also to the overturning action of the forces on the whole structure. These are also at a maximum at the base, and will now be dealt with.

RESISTANCE OF THE GUIDE-FRAMING TO THE BODILY OVERTURNING OF THE STRUCTURE AS A CYLINDER.

As already explained, the standards are compressed on one side of the axis and lifted on the other. The moment of resistance to the bending can be determined as follows:—

(1) Find the moment of inertia of one of the columns round its own axis. Call it I_1. I_1 for round columns $= \cdot 7854 \, (r^4 - r_1^4)$, where r and r_1 = external and internal diameter of the column.

(2) Find the distances of each of the columns (on one-half) from the neutral axis of the whole system, which in this case corresponds with the diameter. Call it $V, V_1, V_2, \ldots$ respectively. (See fig. 25.) These distances can be found by drawing the diagram to scale, or by calculation thus: Multiply the radius of the column circle by the cosine of the angle Q, Q_1, or Q_2, as the case may be.

(3) Find the sectional area of each of the columns. Call it $A, A_1, A_2, \ldots$

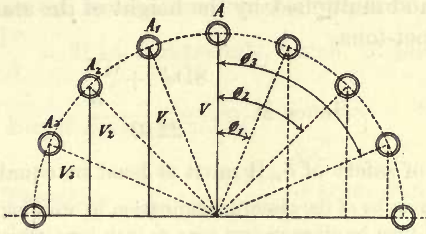

FIG. 25.

The well-known expression for the moment of inertia of the whole system about the neutral axis, is as follows :—

$$I = (I_1 + V^2A) + (I_1 + V_1^2A_1) + \quad . \quad . \quad . \quad .$$

But I_1 and A are the same for each of the columns (when the columns are symmetrical). Therefore we may write the formula—

$$I = n\,I_1 + A\,(V^2 + V_1^2 + V_2^2 \, . \quad . \quad .);$$

n being the number of columns on one side of the axis.

The moment of resistance on one side of the axis—

$$= \frac{IC}{q} = R, \text{ where } R = \text{moment of resistance.}$$

C = 10 for cast iron.
15 for wrought iron.
20 for steel.

q = radius of column circle.

Filling in the value of I, and multiplying by 2 for the two sides of the axis, we have the somewhat clumsy formula—

$$R = \frac{2\,C\,[n \times \cdot 7854\,(r^4 - r_1^4) + A\,(v^2 + v_1^2 + v_2^2 + \, . \, . \, .)]}{q.}$$

If we have the size of the columns given, as well as the other data, we can, of course, see how it compares with the bending moment on the whole structure. We have previously determined the force F, acting at the top of the standards to be (in pounds)—

$$\frac{8Dd^2}{H} + \frac{D^3}{3H}$$

which, reduced to tons, and multiplied by the height of the standard (H), will give the bending moment M, in foot-tons.

$$\text{Hence } M = \frac{8Dd^2 + \frac{D^3}{3}}{2240}$$

If we allow a factor of safety of 5, R must at least be equal to five times M.

NOTE.—All dimensions must be of the same denomination in working these rules—that is, either feet or inches. R and M will then be given in foot-tons or inch-tons, whichever is selected.

The above general formula may be much simplified, as follows:—As the material forming the cylindrical cantilever is disposed regularly around the circle—*i.e.*, the whole of the columns are the same in strength, and spaced at equal distances apart—we may consider the columns as spread out into a thin cylinder, the formula for which is, according to Rankine and others:

$\frac{1}{4} A_1 D_1 C_1 = R$, where $A_1 =$ the sectional area of the whole of the columns.

This may be proved correct, either by working examples both ways, or as follows:—The radius of gyration for a circle turning on its diameter is 0·7071 times its radius, or $0{\cdot}7071q$.

$$\text{The moment of inertia} = (0{\cdot}7071q)^2 \times A_1.$$

$$\text{The moment of resistance} = \frac{(0{\cdot}7071q)^2 \times A_1 \times C}{q}.$$

$$= A_1 Cq \times 0{\cdot}7071^2.$$

$$\text{But } 0{\cdot}7071^2 = 0{\cdot}5, \text{ therefore } R = \frac{A_1 Cq}{2}$$

But we can substitute $\frac{D_1}{2}$ for q.

$$\text{Hence } R = \frac{1}{4} A_1 D_1 C, \text{ as above.}$$

This simple formula will enable us to determine all we want as regards the resistance to the overturning of the structure as a cantilever. Taking a factor of safety of 5, and the ultimate resistance of cast iron, wrought iron, and steel as 10, 15, and 20 tons per square inch respectively, we have for the moment of resistance in foot-tons (*safe*):

$$\text{For cast iron, } \frac{A_1 D_1}{2}\text{; wrought iron } \frac{A_1 D_1}{1{\cdot}5}\text{; steel, } A_1 D_1.$$

A_1 being the sectional area of *all* the columns, in square inches;

D_1 being the diameter of the column circle, in feet.

It will be seen at a glance, how handy and simple these formulæ are, when compared with the elaborate formula previously given.

The simplest expression for the overturning moment of wind and snow has been given as $8\,Dd^2 + \frac{D^3}{3} = M$ in foot-pounds, which, divided by 2240, will give M in foot-tons.

But R should equal M.

$$\text{Therefore} \quad \frac{A\,D_1}{2} = \frac{8\,d^2 + \frac{D^3}{3}}{2240} \text{ (cast iron)}$$

$$\text{Hence} \quad \frac{16\,Dd^2 + \frac{2}{3}\,D^3}{2240\,D_1} = A.$$

But D is nearly equal to D_1 in all cases. So that, for all practical purposes, we may substitute D for D_1; and then, dividing by the number of columns n, we have for the *sectional area required to resist the dead load on a single column or standard*—

$$\text{For cast iron . . } \frac{24\,d^2 + D^2}{3360\,n} = A_1$$

$$\text{For wrought iron . } \frac{24\,d^2 + D^2}{5040\,n} = A_1$$

$$\text{For steel . . . } \frac{24\,d^2 + D^2}{6720} = A_1$$

This sectional area must be added to that already found necessary for resisting distortion; but it may be distributed over the entire section of the standard. To this also might be added something for the dead weight of the column itself, as well as for defects in casting, bolt holes, &c., uncertain contraction, and structural strains partly due to fixing, &c. If of wrought iron, allowance must be made for joints and rivetting, and initial strains due to drawing the work together in rivetting, &c. These, however, are allowed for by substituting D for D_1 in the formula above, as also by the assistance rendered to the framing by its dead weight. (See Note M, page 57.)

When the gasholder acts as a *perfect* cantilever there is very little strain on the standards. But it cannot do so *perfectly*, owing to the elastic nature of the iron, the unavoidable slackness of some of its parts, the effect of temperature (as well as elasticity) in altering the lengths of the parts, the imperfect contact of the bell with the guide-framing, due to the same and other causes, which enhance the strains on *parts* of the framing locally, however slight they may be. Undoubtedly all these influences tend to modify the application of the exact formula. It seems highly probable that the columns against which the holder is pushing would yield, and bend over dangerously, before the hindmost column would be affected to anything like the same extent, although the whole of them are bound together in one circle by the bracing.

In the formulæ now advanced, allowances are made for this, inasmuch as the maximum stresses of both wind and snow are provided for, as acting at one time; and considerable allowance has been made for buckling and the distorting effect of the forces. Any attempt to determine the strains on a holder which disregards the latter, would be, to say the least, extremely dangerous to follow.

Again, it would seem advisable to throw metal into the standards to make them act somewhat as independent posts, so as to relieve the strain on the diagonal bracing, which is very great when required to transmit the strain as a perfect cylinder should do.

STRAINS ON THE BRACING.

The girders and ties—or rather the struts and ties—which brace the whole system of standards into one cylindrical cantilever, are subject to very severe strains, especially when the standards are light. The girders or struts are, of course, in compression, and the ties in tension. The method of finding the strains on the bracing depends upon the following principles, relating to girders, and which are deduced from the ordinary formulæ to be found in most text-books on the subject (Sheild's, D. K. Clark's, and others :—

(1) In a cantilever girder, the strain in the flanges at the abutment equals the sum of the horizontal components of *all* the ties—or, in other words, the strain in the flange at abutment, represents the horizontal shear on all the ties; and if this total shear be divided by the number of ties (inclined the same way), it will give the horizontal shear on each, in the case of a cantilever *loaded at the extremity only.*

(2) If the cantilever be *uniformly loaded* over its entire length, the strain in the ties increases from the end towards the abutment, in the proportion 1, 2, 3, 4, &c., counting from the free end to the abutment.

(3) The strain on the vertical struts, in the case of the load applied at the extremity of the cantilever, is equal to the load throughout; but if the load be uniformly distributed, the strain on the struts increases in the same proportion as the strain on the ties increases—viz., as 1, 2, 3, 4, &c., counting from the free end.

(4) Therefore, when we have the total horizontal shear given, we can determine the strain on the ties and struts, for either a load applied at one end of the cantilever, or for a uniformly distributed load. But to get the direct strain on the ties, the horizontal shear must, of course, be resolved in the same direction as the ties—*i.e.* increased in the same proportion as the inclined length exceeds the horizontal length of tie. A similar course must be applied to the struts.

These principles can easily be proved to be true, so we will pass on to the application of them to the guide-framing; and, in doing so, it must be remembered that the guide-framing is a *vertical* cantilever, whereas the above refer (in the wording) to a *horizontal* cantilever. But it makes no difference; the principles are, of course, equally applicable to either a vertical or horizontal cantilever.

The guide-framing, then, may be treated as a vertical cantilever, subject to horizontal pressures uniformly distributed. The only difficulty that arises is the determination of the distance apart of the *centres of thrust and lift* on either side of the neutral axis.

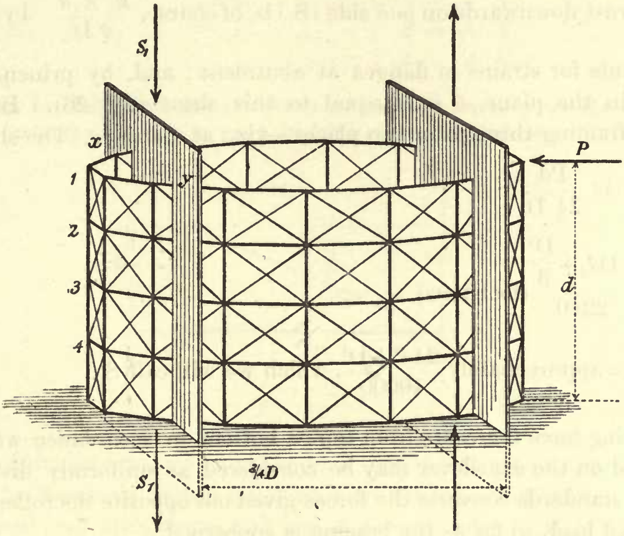

FIG. 26.

In an ordinary lattice girder, we have but two flanges; and the distance apart of these centres is therefore apparent. But, in the case of a gasholder guide-frame, we have *several* flanges as it were on both sides of the axis, corresponding with the number of columns; and the strain on them varying according to their distance from the axis. It is obvious, however, that there must be two points, one on each side of the axis, which we may term the centre of thrust and lift respectively, and which, if found, will enable us to determine the strain on the bracing, because they correspond with the tension and compression flanges in an ordinary girder, and the distance between them corresponds with the *depth* of the girder.

Mr. B. Baker considers these points as determined by the radius of gyration of the column circle (which is 0·7071 times the radius), and then allows a margin for inaccuracies in fixing, as well as for the dependence placed on the bracing for helping the standards to resist distortion, as before explained. But against this we must put the assistance rendered to the bracing by the dead weight of the structure itself, and which, as far as it affects the columns, is refered to in Note M, page 57. Bearing all these points in mind, we shall be quite safe in fixing the distance apart of the vertical shearing planes at three-fourths of the diameter of the holder, or $\frac{3}{4}$ D.

The total thrust downwards on one side (S_1) is, of course, $\frac{P \times d}{\frac{3}{4} D}$ by the ordinary cantilever formula for strains in flanges at abutment; and, by principle 1, the shear on all the ties in the plane $x\ y$ is equal to this shear (fig. 26). But the shearing plane cuts the framing through in two places—viz., at x and y. The shear on the one side, therefore, is $\frac{Pd}{1\frac{1}{2} D}$

$$\text{But } Pd = \frac{8\ Dd_2 + \frac{D^3}{3}}{2240} \text{ (foot-tons)}$$

$$\text{Therefore } \frac{Pd}{1\frac{1}{2} D} = \text{approximately} \frac{24d^2 + D^2}{10000}, \text{ which we will call } S_1.$$

This shearing force increases from top to bottom in accordance with Principle 2, because the load on the cantilever may be considered as uniformly distributed. The stiffness of the standards converts the forces given out opposite the roller carriages only, into a distributed load, so far as the bracing is concerned.

For convenience, we will resolve this total shear into an inclined force, and a horizontal one, as per Principle 4.

In fig. 27, S_1 represents the shear (vertical); T, the inclination of the ties; and B_1, the horizontal struts. Let T be the length of a tie, B the length of a strut, and B_1 the vertical distance between two struts; then—

$$S_1 \text{ resolved into direction } T = \frac{S_1\, T}{B_1}, \text{ call it } X$$

$$S_1 \quad ,, \quad ,, \quad ,, \quad B = \frac{S_1\, B}{B_1}, \text{ call it } Y.$$

Now by Principles 2 and 3 we have for the strains on the ties and struts, supposing there are four sets or panels in height, as in fig. 26—

$$1 + 2 + 3 + 4 = 10.$$

Tension on the top tie, or No. 1 $= \frac{1}{10}$ X.
,, next ,, ,, 2 $= \frac{1}{5}$ X.
,, ,, ,, ,, 3 $= \frac{3}{10}$ X.
,, ,, ,, ,, 4 $= \frac{2}{5}$ X.

Thrust on the top strut, No. 1 $= \frac{1}{10}$ Y.
,, next ,, ,, 2 $= \frac{1}{5}$ Y.
,, ,, ,, ,, 3 $= \frac{3}{10}$ Y.
,, ,, ,, ,, 4 $= \frac{2}{5}$ Y.

Note.—There are two ties in each panel, crossing one another; but only one of them can be under strain at a time, so each must be made to stand the full strain as found above.

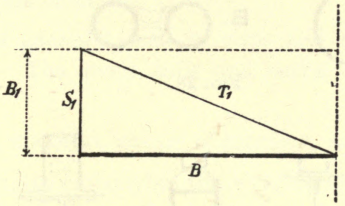

Fig. 27.

In treating of the bracing, we have assumed that it receives no assistance from the side stiffness of the standards, which latter we have treated as only of sufficient strength to resist the vertical load upon them, and the distorting effect. If the standards are excessively rigid beyond what is demanded by the rules laid down, the bracing is relieved proportionally.

The foregoing formulæ given in this article, relate particularly to the complete cylinder type of framing. If the gasholder belongs to the independent post type, or the composite type, the formulæ do not apply. The formulæ then vary according to the number of tiers of girders, the strength of the ties, &c.—in fact, as to how nearly it approaches the cylinder type. We will now give these our attention.

GASHOLDERS OF THE MULTIPOST TYPE.

In determining the strains on gasholders of this type (fig. 38, page 59) we are met with the difficulty of variety in design. We have, indeed, everything from the simple gasholder with vertical posts and no connecting girders or tiers whatever, to that having one, two, three, and occasionally four tiers of girders; the girders being sometimes of wrought iron, deep, strong, and well-attached to the columns, or they may be poor frail things, insufficiently attached, perhaps of cast-iron open-work, practically useless except for ornament and the bare appearance of strength. Then, again, the girders may be either upright, or lying on their sides so as to form a stiff ring; or both plans may be blended in one structure. Then, the columns or standards may be of any variety of shape—round, tripod, or T shape; I shape, diamond, or square (figs. 28, 29, and 30)—all having their peculiarities and influence on the strength of the structure as

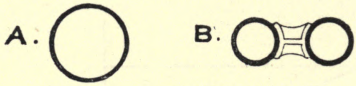

Fig. 28.

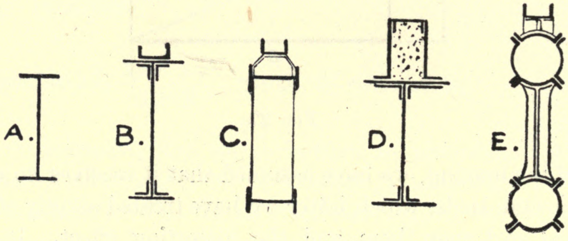

Fig. 29.

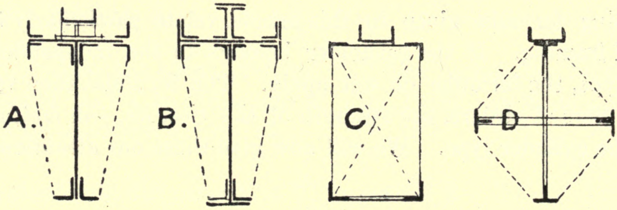

Fig. 30.

a whole. They may be of cast iron, wrought iron, or steel; arranged in pairs or singly; either with or without diagonal rods between them; and perhaps with horizontal bracing at the top—Paddon's ties. We then have the excess of strength in the gasholder bell in cups and curbs lending horizontal stiffness to the frame. (See Note O, page 73.) All this makes it very difficult to give general rules which will apply with equal truth to every variety; but we may lay down the following principles to aid us in classifying the different features and their influences.

The strength of gasholders may be considered to vary as—

1. The number of columns or standards.
2. The transverse strength of one column taken independently of the rest.
3. The total overturning pressure.
4. The number of tiers or girders and their stiffness, and the extent of the bracing (if any) between the columns.
5. Surplus strength of gasholder bell in cups and curbs—stiffness generally—to resist distortion. The more cups and curbs, the greater the resistance to distortion.
6. The workmanship, material, nature of junction, and design of details generally.

We can construct formulæ embodying these variations, which will give the bending moment each column or standard is called upon to resist. It is then, of course, very easy to proportion the column to meet this bending moment, as will be shown when we apply the formulæ to examples.

Let D = the diameter of the outer lift, in feet.
d = the *total* depth of the gasholder when right up, in feet.
N = number of columns.
C = constant, varying according to the design and wind pressures, thus:

For gasholder having guide-framing the *full* height—

3 lifts and	3 tiers girders				= 300
3	,,	2	,,	,,	= 250
2	,,	2	,,	,,	= 200
2	,,	1	,,	,,	= 150
1	,,	1	,,	,,	= 100

In applying these constants, they must be modified as follows:—If the gasholder be well sheltered from wind all round, 25 per cent. may be added to them. If, on the

other hand, it is exposed to great wind pressure, 25 per cent. should be deducted. And in special cases, where erected on the coast (and unprotected in any way from furious gales), they may be reduced as much as 50 per cent., as it is absolutely necessary to err on the side of safety, to allow for contingencies even under the best supervision.

Having modified the constant according to wind pressure, call it C_1; and then still further modify it as follows :—

If diagonal ties, *add* from $\frac{1}{6}C_1$ to $\frac{1}{5}C_1$, according to the strength and attachment of same.

If curbs and cups are very strong, *add* $\frac{1}{10}C_1$.

If girders are shallow, and not well attached or bracketed to columns, *deduct* $\frac{1}{6}C_1$ to $\frac{1}{5}C_1$.

If standards lack lateral or side stiffeners, *deduct* $\frac{1}{5}C^1$.

If workmanship or materials are of inferior character, deduct $\frac{1}{6}C_1$ to $\frac{1}{4}C_1$. (This embraces unfair holes and bad riveting ; loose fitting bolts, instead of rivets ; work unduly strained by drawing together ; ties not taut ; junctions and details generally badly designed and proportioned ; guides out of plumb ; rollers badly adjusted ; &c., &c.)

Then M, the bending moment at foot of one column or standard (in foot-tons) =

$$\frac{D \times d^2}{N \times C}$$

Having determined this, we know, of course, that the moment of resistance, R, of the column or standard must be equal to it.

R, for ordinary round cast-iron columns = approximately,

$$\frac{A d_1}{1\cdot 6}\text{ foot-tons.}$$

Where A = sectional area of column (in square inches),

,, d_1 = diameter of column (in feet).

R, for latticed standards, or web plate standards of symmetrical cross-section, wrought iron = 5 A d_1, steel = 8 A d_1.

Where A = effective sectional area of back flange, in square inches,

,, d_1 = depth of standard from front to back, in feet.

NOTE.—The constants 5 and 8 may well be reduced if the standard be of the lattice type, and the "pitch" of the lattices is excessive.

Cast-iron standards, with open webs and various thicknesses of metal are in every way inferior to wrought-iron ; so we need not consider them. The same remark applies to cast-iron girders.

Where the section of a web-plate standard is unsymmetrical, it requires special treatment. The resistance of one flange must be multiplied by its distance from the centre of gravity of the cross

section of the standard (assumed neutral axis); then the double of this product will give approximately the resistance of the standard to bending (R).

Gasholders with reduced guide-framing should have diagonal ties added to the guide-framing, of sufficient strength to bring them under the cantilever cylinder type described in the third article; and the several lifts must be stiffened up to meet the extra strains, as directed in the second article. Also tangential as well as radial rollers should be adopted, to assist in getting a good fit and grip between the holder and the guide-framing.

Note I.

Iron shortens or lengthens about $\frac{1}{12000}$th part of its length for every ton per square inch strain upon it. This property of the elasticity of iron is very apparent in a large gasholder. For example, we will take the shortening of the top curb of a gasholder 200 feet diameter. The circumference in inches would be 7540, one-twelve-thousandth of which is 0·628 of an inch. Therefore the curb would shorten 0·628 of an inch for every ton strain; and as top curbs are frequently strained up to 4 tons per square inch (sometimes a very great deal more), the total shortening would be at least $2\frac{1}{2}$ inches, which means a reduction in the diameter of more than $\frac{3}{4}$ inch. It follows therefore, that *the top rollers are off the guide face by* $\frac{3}{8}$ *inch all round*, when the holder is right up, and the curb is fully strained. The strain on the top curb is, of course, due to the pull of the top sheets; and this varies according to the pressure of gas within. When the holder is "down," there is practically no strain on the curb; and it is therefore at its full diameter. The roller carriages may be adjusted so that the rollers are absolutely tight against the guides when in this position; but immediately the holder rises, the pull of the sheeting compresses the ring, and so draws off the top rollers—making "play"—and each time the holder picks up weight (that is, cups), the curb shortens and the rollers leave the guides still more. This should not be allowed for by adjusting the rollers when the holder is at its full height, because when the holder descends and the curb swells in diameter, the strains on the rollers would be enormous unless the carriages are very springy, besides over-straining the framing.

Of course, this property of shortening under compression, and lengthening under tension, is applicable to the whole structure; the above has been chosen merely as an illustration. Therefore we see at once that there is no such thing as absolute and perfect fit in a huge structure like a gasholder; and, consequently, it would be very

unwise to construct holders with only a few feet of guide-framing, as they depend upon perfect fit and absolute rigidity in all their parts. It is this same principle that makes it necessary to have the lifts of the gasholder at least one-fifth of the diameter in depth, to prevent tilting, and to economize material.

Again, the *difference in temperature* between winter and summer will cause the lengths of the various parts to vary. They may be $\frac{1}{2000}$th part of their length shorter in winter than in summer.* These variations, due to elasticity and temperature, modify to a certain extent the cantilever treatment of the guide-framing, because of the impossibility of getting each part to *perfectly* do the duty and fill the office expected of it.

Note J.

The pressure of the bottom rollers against the tank guides varies according to the height of the guide-framing. If the guide-framing be carried to the full height, the pressure of the gasholder against it is shown in fig. 31; the wind being uniformly distributed throughout the whole height of the holder, and acting in a horizontal

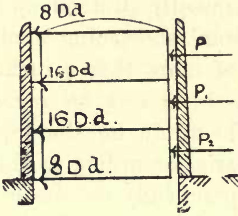

Fig. 31.

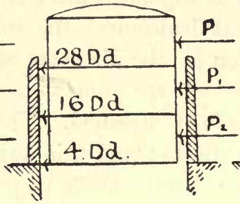

Fig. 32.

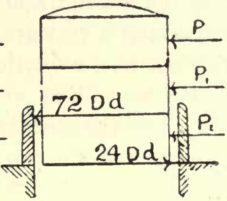

Fig. 33.

direction. The pressure is distributed amongst the rollers on the three lifts *approximately* as shown. We say approximately because, should the rollers on the middle lift be too weak, or yield a little to the strain, it would throw more pressure on the rollers above and below. If the guide-framing be carried to the height of two lifts only, the pressure may be taken as in fig. 32. If the framing stop short at the outer lift, the pressures are indicated in fig. 33.

In all cases D represents the diameter of the holder, and *d* the depth of *one* lift—both in feet. The pressure is the *resultant* pressure in *pounds* distributed on the one circle—not the pressure on each roller. The arrows indicate the direction. The

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* See Barlow's "Strength of Materials," p. 280.

pressures given are those due to the wind only. The effect due to the weight of snow can easily be added, if desired.

It has been suggested that the gasholder has a tendency to fall *against* the wind, because its centre of gravity is above the centre of pressure of the wind. This can never happen as long as the base is restricted from advancing. It is impossible to cause the heavy headed stick shown in fig. 34 to fall *backwards* when struck in the direction indicated by the arrow P, although its centre of gravity is above the point

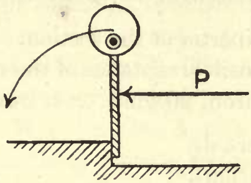

FIG. 34.

struck. It is bound to fall forwards, owing to the restricted base. A gasholder is an analogous case. When subject to a *sudden gust* of wind, it has a momentary tendency to fall backwards, or, more correctly, to thrust the bottom curb suddenly forward, hard against the guides. But as it meets with resistance, the top, of course, goes forward; and, if the wind is a steady, constant push, the pressures given out will be approximately as indicated in the foregoing diagrams.

NOTE K.

Even in the case of a simple plate girder, the exact calculation of the buckling tendency is practically impossible—the extent of stiffening necessary for the web has been determined by experience, and is quite foreign to all ordinary formulæ relating to the strength of girders, which formulæ only provide for the strength of flanges and web to resist the load, omitting the buckling tendency altogether. Speaking on this subject, Weyrauch states that "experiments have long shown that the plate-girder fails first by side buckling; the forces thus arising *elude any systematic investigation.*"* If this be true for a simple plate-girder, how much more so for a complicated structure like a gasholder. In a single column or strut, subject to direct load, the determination of the buckling tendency is very difficult. How much more so, then, for a column

* See "Strength and Determination of the Dimensions of Structures of Iron and Steel," by Dr. J. J. Weyrauch. Box, on "Strength of Materials," also gives numerous examples proving this.

built up of a group of columns, latticed together, and subjected to forces acting indirectly upon them and in various planes and directions. The formulæ given in the article, therefore, are to be preferred to a deep mathematical investigation based on merely theoretical conditions, and which is likely to be very much wider from the truth.

Note L.

The general formula for the strength of a cylindrical cantilever is $\frac{I\,C}{r\,L} = W$.

Where I = moment of inertia of the section.
C = ultimate (tensile) resistance of the material per square inch (say, wrought iron, 20 tons; cast iron, 10 tons; steel, 30 tons).

r = radius (external).
r_1 = radius (internal).
L = length of cantilever.
W = breaking weight, in tons.

Or, filling in the value of I for a circle,

$$W = \frac{r^4 - r_1^4 \times \cdot \text{[illegible]} : 5}{r\,L.}$$

All other rules found in text-books are based upon this, though the way in which they are expressed may vary. Humber, Molesworth, and others, give rules which can be proved to agree with the above.

For very thin cylinders, however, it is not thought necessary to burden the formula with the two radii, as the difference is so slight. Rankine, Clark, Fairbairn, Trautwine, and others, therefore substitute the following approximation :—

$$\frac{A\,D\,C}{4\,L},\ \text{or}\ \frac{\cdot 7854\,D^2\,t\,C}{L}$$

Where A = the sectional area in square inches,
D = the diameter of the cylinder,
t = the thickness.

As regards the constant C, Fairbairn found, from several experiments, that it was about 13 tons per square inch for wrought iron (Trautwine gives 21 tons).

Experiments have been made with thin wrought-iron tubes, varying from 12 inches to 24 inches diameter, and from $\frac{1}{27}$ to $\frac{1}{8}$ inch thick; and it was found that, as the thickness is reduced, the strength decreases at a greater ratio, and that the strength doos not advance exactly as the diameter, but at a somewhat less ratio.

The general formula when applied to the experimental 24-inch diameter beam gives a breaking weight about double of that at which the tube actually broke; and the experiments go to prove that, as the diameter increases, the formula becomes more and more unreliable—the divergence accelerating rapidly; this being due to the fact that the formula does not provide for buckling or lateral stiffness. Mr. B. Baker, Mr. D. Kinnear Clark, and others, draw attention to this omission in the general formula.*

In the case of an iron ship, the skin is more than strong enough to take the direct strain upon it; but over and above this, it is stiffened by stays. According to Rankine, the space between the stays should not exceed (say) 40 times the thickness of the skin; otherwise the skin would *yield by buckling*.† The same applies to very hollow beams. They must be stiffened up, or they will yield by *buckling;* and for this the ordinary formula makes no provision. We, therefore, see its inapplicability to the gasholder for determining the strains. Something more is wanted to go hand in hand with it, and that is an allowance for buckling, distortion, or, as it is sometimes called, *wrinkling*, which allowance has been made in these articles.

Note M.

The columns on the lifting or tensile half of the cantilever are, of course, aided by their own weight, and the weight of the allied framing. The columns near the axis have very little lifting force upon them. Consequently their own weight more than balances it; but as the columns recede farther from the axis, the lifting strain increases until it exceeds the weight of the column. The actual upward lift on the outermost column is, of course, the difference between the calculated lift, and its own weight; assuming the structure to be a perfect cantilever. The columns on the crushing side of the cantilever guide-framing are, of course, further strained by the addition of their own weight. As the wind may blow from any quarter, all the columns must be of equal strength, as each in turn may be the most severely strained one.

The strength of a column is, of course, increased to a much greater extent by adding to the sectional area than it is impaired by the additional weight. Again, the heavier the structure, the greater is the dead weight to set in motion by the capsizing forces. It is to this, added to their individual tranverse strength, that the columns in the old style of guide-framing mainly owe their stability.

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* See "Rules and Tables for Mechanical Engineers," p. 512.

† See Rankine on "Shipbuilding."

FOURTH ARTICLE.

EXAMPLES AND CONCLUSIONS.

We will now briefly recapitulate what has already been advanced.

The first article was an inquiry into the general principles involved in the stability of gasholders, and the effect produced by shortening the guide-framing. It was proved that in any gasholder the depth of each lift must be equal to at least one-seventh the diameter; and that *under certain conditions* it may be admissible to reduce the height of the guide-framing to that of the depth of the outer lift only, but no shorter.

The second article treated of the first condition necessary for the stability of gasholders having reduced guide-framing—viz., that *each lift must be rigid in itself, and unable to distort under the strains induced.* We gave rules for determining the magnitude and character of the extra strains induced by this method of construction, illustrated

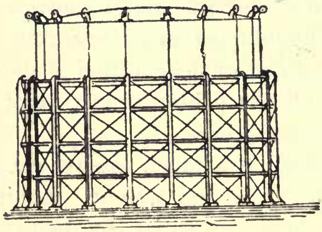


Fig. 35.

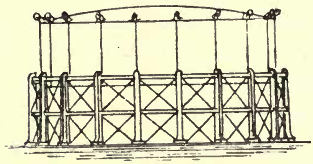


Fig. 36.

by examples; and found as general results that in three-lift gasholders the guide-framing must reach *at least as high as the top of the middle lift* when the bell is right up (fig. 32), otherwise the holder would be unsafe; and that double-lift gasholders could be made with the guide-framing stopping short at the outer lift, providing the depth of each lift is fully one-fourth of the diameter.

In the last or third article, we considered the second condition necessary for the stability of gasholders with foreshortened guide-framing—viz., that *the guide-framing itself must be perfectly rigid and unyielding*, otherwise it will admit of the projecting lift or lifts swaying over dangerously. We resolved that it was practically a matter of strength, or of determining the strains, and then designing the guide-framing to meet them. We divided gasholder guide-framing into two distinct classes—viz., the simple cylinder and the multipost types. (See Note N, page 72.) We then demonstrated the

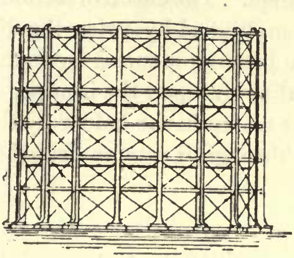


FIG. 37.

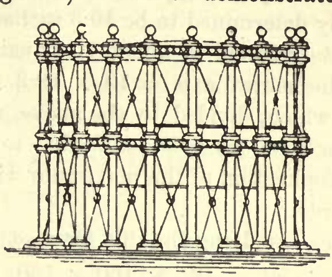


FIG. 38.

principles to be observed in finding the strains, and deduced simple, practical rules for gasholders of both types (figs. 35, 36, 37, and 38).

We will now apply the rules for the strength of guide-framing to a few actual examples; concluding with a summary of the whole question.

CANTILEVER TYPE.

EXAMPLE I.—SOUTH METROPOLITAN GASHOLDER, OLD KENT ROAD. DESIGNED BY MR. GEORGE LIVESEY (I SHAPE, WEB-PLATE STANDARD, *see* FIG. 29 C, page 50.)

D (the diameter of gasholder)	=	214 feet.
H or d (the *total* height of holder)	=	160 ,,
N (the number of standards)	=	24 ,,
B (the distance centre to centre of standards)	=	$28\frac{1}{2}$,,
A (the *effective* sectional area of back flange)	=	10 sq. inches.

Now applying formula for bending moment, due to distorting influences,*

$$\frac{B\,H^2}{270} = \frac{28\frac{1}{2} \times 160 \times 160}{270} = 2702 \text{ (inch-tons).}$$

The standard being in effect a plate girder, and the front flange having so much

* See the last article for method of treatment.

more material in it than the back flange, the neutral axis will not pass midway between the flanges, but through the centre of gravity of the cross section of the standard. Therefore in determining the moment of resistance of the standard, we must take the sectional area of either flange, and multiply it by its distance from the neutral axis. Twice the product into the resistance of the material (per square inch) will give the moment of resistance (R) very nearly.*

In this particular example the centre of gravity of the cross section of the standard is easily determined to be 19·3 inches from the *back* flange. The effective sectional area of the *back* flange is about 10 square inches. This multiplied by twice the distance from the neutral axis $= 10 \times 19{\cdot}3 \times 2 = 386$. The bending moment we found to be 2702, which, divided by the above, will give the actual strain upon the iron per square inch, or 7 *tons per square inch*, due to distorting strains set up in the holder by the one-sided application of the maximum wind pressure, and through it communicated to the standards.

Now, applying the rule for *dead thrust*, we have

$$\frac{24d^2 + D^2}{5040\ N} = \frac{(24 \times 160 \times 160) + (214 \times 214)}{5040 \times 24} = 5\tfrac{1}{2} \text{ square inches required.}$$

The spare section about the neutral axis of the web plate in the standard is competent to meet this dead thrust; the total section of web being equal to 10 square inches fully.

Strain on Ties and Struts.—Referring to the third article, we find S_1, the vertical shear =

$$\frac{24d^2 + D^2}{10{,}000} = \frac{24 \times 160 \times 160 + 214 \times 214}{10{,}000} = 66 \text{ tons.}$$

which, resolved in the direction of tie $= 66 \times 2{\cdot}05 = 135$ tons.

" " " strut $= 66 \times 1{\cdot}75 = 115$ tons.

There are five bays of double bracing =

$$1 + 2 + 3 + 4 + 5 = 15.$$

Strain in—			Effective Section allowed.
First or top set	$= \frac{1}{15} \times 135 = 9$ tons	2 bars	$4 \times \frac{5}{8} = 4$ sq. ins.
Second " "	$= \frac{2}{15} \times 135 = 18$ "	"	$5 \times \frac{5}{8} = 5$ " "
Third " "	$= \frac{3}{15} \times 135 = 27$ "	"	$6 \times \frac{5}{8} = 6$ " "
Fourth " "	$= \frac{4}{15} \times 135 = 36$ "	"	$7 \times \frac{5}{8} = 7$ " "
Fifth or bottom	$= \frac{5}{15} \times 135 = 45$ "	"	$8 \times \frac{5}{8} = 8$ " "

* This is not strictly correct; but it is very near the truth.

The strain per square inch is, therefore, $2\frac{1}{4}$ tons on the top set ; and increasing to fully $5\frac{1}{2}$ tons per square inch on the lowermost set, which is quite safe.

Strains on the Struts—

$$\begin{array}{lcl} \text{First or top ring} & = \frac{1}{15} \times 115 = & \text{(say) 8 tons.} \\ \text{Second} \quad ,, & = \frac{2}{15} \times 115 = & ,, \ 16 \ ,, \\ \text{Third} \quad ,, & = \frac{3}{15} \times 115 = & ,, \ 23 \ ,, \\ \text{Fourth} \quad ,, & = \frac{4}{15} \times 115 = & ,, \ 30 \ ,, \\ \text{Fifth} \quad ,, & = \frac{5}{15} \times 115 = & ,, \ 38 \ ,, \end{array}$$

The effective sectional area of each strut is something like 15 square inches ; so that in the lowermost one, it is only about $2\frac{1}{2}$ tons compression per square inch, whereas in the top ring it is only about $\frac{1}{2}$ ton. (See Note P, page 73.)

EXAMPLE II.—LARGE GASHOLDER AT BIRMINGHAM. DESIGNED BY MR. CHARLES HUNT.

$D = 233$ feet. d or $H = 150$ feet. $N = 26$. $B = 29$ feet.

$K = 60$ inches $A = 16$ square inches (effective).

$$\text{Applying the formula } \frac{B\ H^2}{180\ K} \text{ we have } \frac{29 \times 150 \times 150}{180 \times 60} = 60\tfrac{1}{4} \text{ tons.}$$

Allowing a strain on the iron of 5 tons per square inch, we require say 12 square inches in each flange. The actual effective area is 16 ; so that we have a margin of 4 square inches in each, or a total of 8 square inches to meet the thrust and lift strains. These by the formula,

$$\frac{24\ d^2 + D^2}{5040\ N} = \frac{24 \times 150 \times 150 + 233 \times 233}{5040 \times 26} = 4\tfrac{1}{2} \text{ square inches required.}$$

One boom only is therefore sufficient to meet these strains. The ties in this case attach to the back flange or boom of the standard ; so that the strains they induce are chiefly carried or transmitted by that flange.

As regards the bracing between the standards, the number of panels or sets of struts and ties are the same as in the last example—viz., five ; and on applying the formulæ, it will be found that the strains are almost precisely the same, bar for bar, as for the previous example, but the sections of iron allowed are a little stronger. We need not repeat the method, as it would practically agree with the above.

In both these examples, we note that the ties and struts in the upper part appear much stronger than needful to meet the estimated strains ; but this is correct for the following reasons :—

(1) The excess of strength in the upper struts, together with the wind ties (sometimes called Paddon's ties), helps to resist the tendency of the framing to distort out of

shape horizontally, as they act like so many stiff rings or curbs. This help is most needed at the top, because the lower portion of the cylinder of guide-framing is fixed to the solid tank, and cannot therefore distort out of the circle; but the upper part depends upon the stiff rings not only in the holder, but in the framing itself quite as much as upon the stiffness of the standards acting as independent posts or cantilevers.

(2) The wind pressure and other overturning forces act upon the standards through the roller carriages, which, of course, are at points up the standard; and therefore, properly speaking, the forces are not uniformly distributed. A great deal of the force is given out by the top rollers at the top of the framing, making the upper part of the standard like a beam loaded at one end only; and therefore increasing the strain on the top bays. These are good reasons for the apparent excess of strength.

Note.—It is, of course, an easy matter to determine the strains due to the forces acting at points up the front of the standards, instead of being distributed as we have taken them; but for all practical purposes, we may take as a reliable rule that the top ties should not be less than half the sectional area of the bottom set—the others being proportionally treated. The struts should be of equal strength and stiffness throughout, so as to resist distortion.

EXAMPLE III.

The largest gasholder in the world is the four-lift one erected at the East Greenwich works from the designs of Mr. George Livesey. The guide-framing is carried to the full height of the gasholder, and consists of 28 wrought-iron web-plate standards of I section (see fig. 29 D), braced together into one huge cylinder by six tiers of struts and systems of diagonal bracing.

D	(the diameter of gasholder)	= (say)	250	feet.
H	or d (the total effective depth)	= —	180	,,
N	(number of standards)	= —	28	,,
B	(centre to centre of standards)	= (say)	28	,,

Assuming that the top curb is able to offer resistance to distortion at the top, aided by the Paddon's ties, we have—

$$M = \frac{BH^2}{270} = \frac{28 \times 180 \times 180}{270} = 3360 \text{ inch tons} = \text{the bending moment on}$$

each standard.

The cross section of the standard displays a great deal more material in the front than in the back flange; and, being a web-plate girder, the neutral axis will fall nearer to the front flange, or about 20 inches from the back flange. The sectional area of the back flange is fully 11 square inches effective. $11 \times 20 \times 2 = 440$.

$$\frac{M}{440} = \frac{3360}{440} = 7 \cdot 6 \text{ tons per square inch.}$$

This is the strain on the flanges of the standard, due to the *distorting* influence of the maximum wind pressure on the whole gasholder.

The dead thrust on one standard, due to the overturning action of the wind, requires by the formula—

$$\frac{(24 \times 180 \times 180) + (250 \times 250)}{5040 \times 28} = \text{nearly 6 square inches.}$$

The sectional area of the web is 9 square inches. The metal about the neutral axis, together with the concrete filling in the front guide, will therefore fully meet this strain of dead thrust on the standard, due to the *overturning* action of the wind.

We still have the bracing to treat of. Applying the formula for vertical shear—

$$S_1 = \frac{24d^2 + D^2}{10{,}000} = \frac{(24 \times 180 \times 180) + (250 \times 250)}{10{,}000} = 84 \text{ tons.}$$

The bracing between the standards consists of six tiers of horizontal struts and two distinct series of cross ties; one set being of steel (represented in fig. 39 by the thick lines), and the other of wrought iron (indicated in the illustration by thin lines).

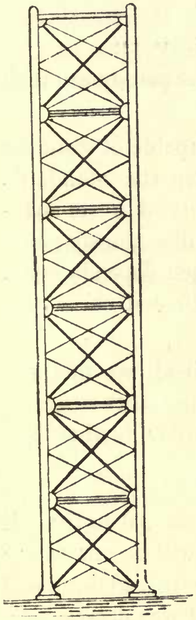


Fig. 39.

We will deal with each series separately, and as resisting the whole vertical shear (84 tons). Taking the main steel ties first, the 84 tons resolved in the direction of these main ties = 116 tons. As there are six panels of ties in the height, we have—

$$1 + 2 + 3 + 4 + 5 + 6 = 21.$$

Strain in—

			Square Inches.
Top tier	$= \frac{1}{21}$ of 116 = 5·5 tons.	Effective section of tie allowed.	$= 2\frac{1}{2}$
Second ,,	$= \frac{2}{21}$ of 116 = 11·0 ,,		= 3
Third ,,	$= \frac{3}{21}$ of 116 = 16·6 ,,		$= 3\frac{1}{2}$
Fourth ,,	$= \frac{4}{21}$ of 116 = 22·2 ,,		= 4
Fifth ,,	$= \frac{5}{21}$ of 116 = 27·6 ,,		$= 4\frac{1}{2}$
Bottom ,,	$= \frac{6}{21}$ of 116 = 33·2 ,,		= 5

The lowermost ties are 10 in. by $\frac{5}{8}$ in. The effective sectional area after allowing for the riveted junction, equals (say) 5 square inches, which is therefore less than 7 tons per square inch— a very safe working strain for steel. The ties decrease an inch in width every bay; the topmost being 5 in. by $\frac{5}{8}$ in. There is therefore but little more than 2 tons per square inch on the top ties; the balance of strength going towards preservation of form, &c., as already explained.

We see from the foregoing that, providing the standards are stiff enough in themselves, the main steel ties are all that would be required. But in this case they would lack lateral stiffness, unless braced intermediately—the pitch of the main steel ties being about 30 feet; and we must remember that the formula applied to the standards assumes that they (the standards) are thoroughly lashed together into one complete cylinder.

We will now consider the whole shear (84 tons) as coming upon the secondary ties only. Resolving it into the required direction, we have 156 tons, and halving it, because there are two pairs of ties in each panel, we get 78 tons as the inclined pull to be split up amongst the six panels, or strain on

Top tiers	$= \frac{1}{21} \times 78 =$	$3 \cdot 7$	sectional area allowed	$= 2\frac{1}{2}$	sq. ins.
Second ,,	$= \frac{2}{21} \times 78 =$	$7 \cdot 4$	,, ,,	$= 3$	,, ,,
Third ,,	$= \frac{3}{21} \times 78 =$	$11 \cdot 1$	,, ,,	$= 3\frac{1}{2}$	,, ,,
Fourth ,,	$= \frac{4}{21} \times 78 =$	$14 \cdot 9$	,, ,,	$= 4$	,, ,,
Fifth ,,	$= \frac{5}{21} \times 78 =$	$18 \cdot 5$	,, ,,	$= 4\frac{1}{2}$	,, ,,
Sixth ,,	$= \frac{6}{21} \times 78 =$	$22 \cdot 2$	,, ,,	$= 5$	,, ,,

The strain on the most severely strained tie is thus barely $4\frac{1}{2}$ tons per square inch —a very safe strain for wrought iron in tension.

We see, therefore, that we have two distinct series of ties, each capable of standing the entire strain. No doubt the object has been, not only to give the standards greater support laterally, but likewise to provide against the possibility of a tie snapping; because if one tie snaps, it might upset the whole structure—like the snapping of one link in a chain. In the cantilever form of construction, so much depends upon the ties being taut, and not giving way, unless the parts are duplicated as in this instance.

As regards the struts, by applying the process already described, we find the strain on the bottom one = 22 tons compression. The section of the strut is ample and well adapted by its form to resist this thrust; so we need not enter further into details.

The foregoing are examples of holders having the guide-framing carried to the full height, and with wrought-iron framed standards. The next example will be one where the *guide-framing stops at the middle lift*, and has cast-iron columns braced into one cylinder. It is the first and only one of the kind in existence, and was designed by Mr. George Livesey.

EXAMPLE IV.—ROTHERHITHE GASHOLDER.

$D = 153$. d. or $H = 75$. $N = 18$. $B = 30$. d_1 (diameter of column) $= 36$ inches. Thickness (say) 1 inch. Two tiers of girders to act as struts, with strong flat-iron ties between.

Applying the formula, we find that the sectional area of one column required to meet the distorting strains only equals—

$$\frac{1 \cdot 6 \ B \ H^2}{130 \ d_1} = \frac{1 \cdot 6 \times 30 \times 75 \times 75}{130 \times 36} = 58 \text{ square inches.}$$

Sectional area required to meet direct thrust and lift strains for one column equals—

$$\frac{24 \ d^2 + D^2}{3360 \times N} = \frac{24 \times 75 \times 75 + 153 \times 153}{3360 \times 18} = 2\tfrac{1}{2}$$

Making a total sectional area of at least $60\frac{1}{2}$ square inches required when the columns are braced together so as to form one complete cylinder cantilever. The actual sectional area of the column is about 137 square inches, which is, therefore, more than sufficient.

In working the strains on the bracing, we must, for convenience, assume the guide-framing as reaching the full height of the holder, which would make it three bays. The reason for this is that the strain on the bottom set of diagonal ties is the same as if the guide-frame ran to the full height.

$$S_1 = \frac{24 \ d^2 + D^2}{10{,}000} = \frac{24 \times 75 \times 75 + 153 \times 153}{10{,}000} = 15\tfrac{3}{4} \text{ tons.}$$

This, increased in the proportion that the tie bears to the pitch, equals for the ties (or X) 25 tons, and for the struts (or Y) 19 tons.

$$1 + 2 + 3 = 6.$$

Upper ties $= \frac{2}{6}$ of $25 = 8\frac{1}{3}$ tons or (say) 2 sq. in. required.

Bottom ties $= \frac{3}{6}$ of $25 = 12\frac{1}{2}$,, ,, 3 ,, ,,

Section allowed *upper tie* $= 5 \times \frac{5}{8}$ flat ,, $2\frac{1}{2}$ sq. in. effective.

,, ,, *bottom* ,, $= 6 \times \frac{5}{8}$,, ,, 3 ,, ,,

Thrust on struts $= 6\frac{1}{2}$ and $9\frac{1}{2}$ tons respectively. The girders are amply strong to meet this.

INDEPENDENT COLUMN GASHOLDERS.

EXAMPLE I.

We will take a treble-lift gasholder having cast-iron columns 3 feet diameter, and three tiers of wrought-iron trellis girders, braced with light ties, all of best workmanship and design, and subject to ordinary inland wind pressure:

$$D = 150. \quad d = 105. \quad N = 18.$$

Now, to apply the formula $\frac{D \times d^2}{N \times C}$, we must first determine C, in accordance with the rules in the preceding article.

For three lifts and three tiers girders	=	300
Add one-fifth for diagonal ties	=	60
Add stiffness of cups, &c., one-tenth	=	30
		390
Deduct for shallow girders unbracketed, one-fifth		60
		330 = C.

The bending moment on one column is therefore—

$$\frac{150 \times 105 \times 105}{18 \times 330} = 278 \text{ foot-tons.}$$

The moment of resistance of a cast-iron column 3 feet diameter, $1\frac{3}{8}$ inch thick, by the rule—

$$\frac{A\ d}{1{\cdot}6} = \frac{150 \times 3}{1{\cdot}6} = 281 \text{ foot-tons,}$$

which is practically what is required. But to allow for inaccuracies in casting, contraction strains, &c., it would be as well to make them (say) $1\frac{1}{2}$ inches thick at the base.

EXAMPLE II.

If the same size gasholder as the last be constructed with 18 wrought-iron framed standards (**I** shape), instead of cast-iron columns, C in the formula must be reduced to 300, to allow for the flexibility of the standards sideways, &c. This will increase the bending moment to 306 foot-tons on one standard. Now, supposing the standard to be 5 feet deep from back to front, we have $\frac{306}{5}$ = (say) 61 tons strain on one flange, which at 5 tons per square inch, gives at least 12 square inches required. This may be met

by a 12-inch by $\frac{1}{2}$-inch table plate, and two angle-irons 4-inch by 4-inch by $\frac{5}{8}$-inch, which together would give, after deducting rivet-holes, &c., about 12 square inches effective area.

NOTE.—The only objection to I-shaped standards is that they lack lateral stiffness. Diagonal bracing should, therefore, be adopted; and either the distance from tier to tier of the girders should not be too great, or the bracing between the standards should be double. Standards should also be strutted to the girders horizontally.

T-shaped standards are much in favour, because they are very stiff sideways. The front member does its share of the work, and relieves the diagonal ties of much strain. In fact, the standard becomes a double one, so to speak. It offers resistance both radially and tangentially; and in determining R, the resistance of the two members, both front and back, must be added together. But in doing so, only half of the theoretical resistance of the front member should be taken as effective.

CONCLUSIONS.

Having now given the method of determining the strength, or, in other words, the stability of a gasholder, and illustrated it fully by examples, we are in a position to answer for the safety of any existing structure, or, on the other hand, to design any gasholder having one or several lifts, with either partial or complete guide-framing.

The height to which the guide-frame must extend, we find does not depend upon considerations affecting the guide-framing itself; but it is limited rather by the bell or floating part of the holder.

We find that, as regards the guide-framing itself, it might very well stop short at the outer lift of any gasholder, no matter what size or how many lifts, because, when we leave out of consideration the help it receives from the stiffness of the curbs, cups, &c., of the bell, the strain on the guide-framing is the same *theoretically* as it would be if the frame extended to the full height of the gasholder. Practically, however, there is more liability to distortion ; and consequently the rules given in the third article made provision for this. We may conclude that, as far as strength is concerned, it is not the guide-framing itself that draws the line for the reduction of its height ; it is the holder or bell working within it which decides the question.

As demonstrated in the second article, when treating of the bell, it is not safe to have more than one lift free in a three-lift holder, unless the curbs, cups, and sheeting are made abnormally heavy, to meet the severe racking strains, let alone the flexibility of the structure.

But apart from the question of mere strength and safety, there is that of expediency. Although we have determined that it is quite possible, under certain conditions, to reduce the height of the guide-framing as much as two lifts out of three, yet we must still ask, Is it practicable or workable ? and, Will it pay ?

The following are amongst the most serious objections :—

1. The extra weight of iron required both in the bell and the guide-framing would in all probability exceed the weight of the part of guide-framing done away with.

2. It is taking away weight from the still, stable guide-framing, and throwing it into the moving and working part of the holder. The delicately-adjusted light series of cylinders are then called upon to resist all the strains; and must therefore be converted into a heavy, stiff, framed girder, trussed wherever needed to make up for the abolition of external support.

3. The increased weight of the floating holder will give much greater back-pressure upon the exhauster—a constant expense.

4. Racking and twisting strains are brought to bear upon the holder which it never suffers when the guide-frame reaches to the full height.

5. There is also much extra strain on all rollers, axles, and working parts, detrimental to its free easy working, and increasing the wear and tear.

6. The top curb must resist all distorting strains without assistance from the guide-framing, and *vice versâ*.

7. Perfect adjustment of rollers, both inside and out, is an essential condition; and they must be maintained hard against the guides. This not only means extra trouble and expense periodically; but if neglected, it endangers the whole structure, and this means so much more anxiety for the managers of the works. In the old style of gasholders, an inch or two of play would not be so dangerous as $\frac{1}{8}$ inch would be in the new.

8. The thrust of rollers against the guides in the outer lift would be very great; necessitating stronger guides, rollers, &c., and outside rollers on the outer lift.

9. A gasholder having guide-framing the full height is much more handsome in appearance.

Many of the objections stated against the reduction of guide-framing by two lifts apply (although in a less degree) to its reduction by one lift. There would be no danger, however, if constructed properly; and it is a matter of calculation only as regards economy. The curbs, cups, sheeting, axles, carriages, &c., being increased and stiffened to suit, are set against the saving (if any) in the guide-framing, and possibly less labour in erection. The workmanship and erection must be very carefully watched, as so much depends upon perfect adjustment of all the parts.

In any case there would appear very little advantage to be gained by reducing the guide-framing; because the extra risk and anxiety, and constant costly examination necessary, would counter-balance much of the possible economy in the first instance.

To sum up then—

1. Each lift in any holder must exceed one-seventh of the diameter in depth.
2. It is not possible to make a reliable, healthy, and cheap holder of three lifts, with two of them "free."
3. It is possible to make a three-lift holder with one lift free, and it may be cheaper; yet we find there are many drawbacks.
4. Gasholders with guide-framing of less height than that of the outer lift (fig. 40) do not bear consideration in the light of the principles set forth in these articles. They must, therefore, be struck out of the category of practical engineering altogether.

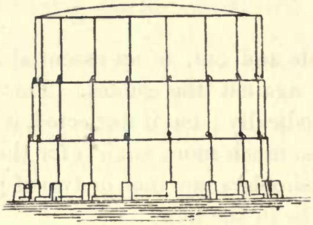


FIG. 40.

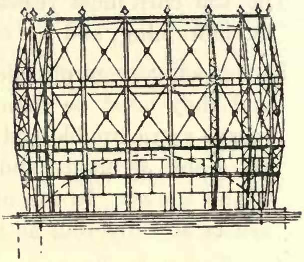


FIG. 41.

The following should be particularly noted:—If it were not for the buckling and distorting tendency of the gasholder and its framing, the columns or standards could be made very light indeed—in fact, the sectional area of each would only need to be but a few square inches; and as far as strength goes, it would be immaterial whether we made the guide-framing a simple cylinder of sheet iron, very thin, or divided the cylinder up into posts (standards) and connected these posts together with bracing of sufficient strength to make up for the absence of the thin sheet-iron web. The more we approximate to the merely theoretical requirements, the nearer we approach the simple thin cylinder, which, if we made the gasholder several hundred feet in diameter, would answer the requirements of the ordinary formula for strength of cylindrical cantilever, if made the thickness of drawing paper! Of course, if it were not absurd from a practical point of view to act upon this, we should have but little need of guide-framing at all—provided absolutely perfect workmanship and exact fit could be relied upon—because the gasholder bell itself would be excessively

strong for the purpose, and a few feet of guide-frame, just to hold it in position, would be all that would be required. (See fig. 40.) But we all know that such a thing would not—to put it mildly—be very good engineering; and for one simple reason: No allowance is made for the buckling and distorting tendencies; and in all, especially in large structures, this becomes a very important item. It has been treated as such in these articles.

It may be asked, Why cannot the floating holder itself be so stiffened up internally and externally with vertical stays, strong girder rings, ties, &c., as to make external support (beyond a few feet at the base) unnecessary? As far as mere theoretical strength is concerned, it *could be so;* but it would be very impracticable for many reasons—

1. Because of the excessive weight to be thrown into the holder. It is, in fact, putting the weight of the usual external guide-framing into the framework of the holder, in order to resist distortion, &c.
2. The material is not so well disposed; having no base to stand upon.
3. The elasticity and variation in length of iron, &c.—leaving out other reasons—make it *impossible* to attain the absolutely necessary conditions of *perfect fit* and *perfect rigidity.*

These are only a few of many reasons, which have already been advanced in former articles against such a proposal.

It is perhaps necessary to remark that, though the force of wind to which a structure may be exposed cannot be given exactly, yet this does not affect in any way what we have done. All the doubt which may be expressed concerning the wind pressure acting on a gasholder is equally applicable to the wind pressure on a bridge, or any other large and exposed structure. The force of wind has to be met in both cases; but on this account we need not assume that it is impossible to determine the strains on either the one or the other. All we have to do is to determine the strains due to what we consider the maximum uniform wind pressure that is ever likely to come upon it. This may be 20, 30, or 40 lbs., whichever we please; it makes no difference to the method. In our case we have taken about 30 lbs. as the maximum, and constructed all the formulæ accordingly; and, of course, if the structure defies the maximum, we need not trouble ourselves about the lesser strains—they are covered by it. It is a very simple matter to modify the formulæ to suit any desired wind pressure.

The foregoing articles treat chiefly of the "Reduced Guide-Framing" type of holder, which is more complicated than the old style; but the principles laid down,

together with the rules here given, should enable anyone with ordinary engineering knowledge to design either the one or the other. Sufficient allowance is made in them to cover all ordinary conditions of working, which makes the treatment of much greater practical value, than an abstruse theoretical demonstration, based on merely theoretical conditions. It has been the author's endeavour throughout to place the subject in as simple a light as possible by employing none but the simplest rules and principles in elementary mechanics and mathematics.

⁂ *Note on Mr. Gadd's Gasholder.*—It is, of course, evident that the method of determining the strains demonstrated in these articles, refers to gasholders having *vertical* guides. Since these papers were written Mr. Gadd has proposed to construct gasholders with *inclined* guides. This is a radical departure from all previous practice, and involves a somewhat different method of treatment; it being asserted that, with inclined guides, the base of the holder will always be maintained in a horizontal position and may be considered as "fixed."

Note N.

Other forms of gasholders, besides those treated of in these papers have been proposed; but they have not met with much favour. Notably, the gasholder having the guide-framing attached to, and supported by, the tank only (see fig. 41), and having a

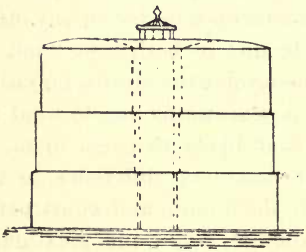


Fig. 42.

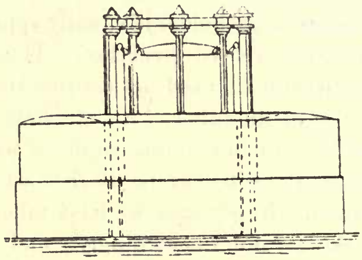


Fig. 43.

domed bottom tank, as described by Professor Otto Intz. Also the central column gasholder and the annular gasholder (see figs. 42 and 43) treated of by Barker, Wyatt,

Meigel and Couffinal, and others. There are so many things against them that they are not likely to make very rapid strides. We may at some future time consider these forms of gasholders more minutely.

NOTE O.

Gasholders without any connection between the standards are never made now; so we need not consider them. Gasholders with twin columns are rare. For all practical purposes, in determining the strains, the columns may be treated as equally divided round the circle, instead of being in pairs; and then the rules which apply to the ordinary construction will likewise apply for this. It is an expensive and unnecessary mode of construction. The object in making them in *pairs* appears to be to get strength with several light columns, in preference to half the number of heavy ones, as well as to avoid cutting up the gasholder into so many narrow bays. Frail cast-iron girders with open webs may also be struck out, as being unreliable and out of date.

NOTE P.

In gasholders of the cantilever type, which depend so much upon the efficiency of the bracing between the standards, the ties should, if they cannot take hold of both flanges of the standards (*i.e.*, front and back), attach to the *heavier* flange, if possible; otherwise the weaker flange has to transmit the force through the web to the strong one. It should be the reverse—viz., what the strong flange cannot resist itself, it should pass on to the light.

AN INVESTIGATION INTO THE

STRAINS UPON THE TOP CURB OF A GASHOLDER,

WITH REMARKS ON CONSTRUCTION, Etc.

[Reprinted from the Transactions of The Gas Institute for 1882.]

THE strain is a compound one; that is, there are several forces acting upon the curb, varying in magnitude and direction.

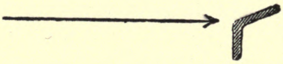
These forces may be classified as follows:—

I. The pull of the top sheets acting at the curb, tangential to the sheeting at the junction with the curb. This strain is caused by the pressure of the gas lifting the holder.

We will call it S.

II. The strain due to the pressure of the wind upon the sides, acting horizontally. This strain I have taken at 26 lbs. per square foot.

We will call it P.

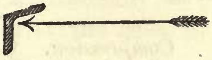


26 lbs. per square foot is the maximum effective pressure, allowing for the cylindrical form of surface impinged against by the wind. This agrees very closely with the paper on "Gasholder Construction" in the *Journal of Gas Lighting*, for April 19, 1881. (See also "King's Treatise on Coal Gas.")

III. The weight of the side sheets, outer lifts, &c., acting downwards in a vertical direction.

We will call it W.

IV. The pressure of the gas from within upon the side sheets.

We will call it F. 

I have not met with any rules which take account of this force; but I cannot help thinking that it would be right to allow something for it, more especially if the vertical stays are attached all the way up to the sheets. Firstly, because the pressure of gas on the sides must be transmitted partially by the stays to the top curb and cup; secondly, suppose the top curb to yield to compression, it must *draw in* the sheets at the sides, and so throw them into compression, thus absorbing any tensile strain that may be upon them.

Note.—In this paper the guide framing is assumed to be perfectly self-supporting; *i.e.*, not depending upon the gasholder for maintaining its form as a regular polygon. Should the curb have to *assist* the guide framing, an allowance should be made for it in designing the curb.

It will be seen, by glancing at the directions of the forces S, P, and W, shown above, that their *resultant* must be in such a direction as to cause *compression* in the top curb. The force F is very slight compared with these; consequently it will not alter the direction of the resultant. The curb must, therefore, yield either by buckling or by compression.

Buckling.

Buckling can only be caused by there being too little lateral stiffness.

Buckling would not occur through F (the pull of top sheets), as it is constant all round, and, in a measure, self-supporting; but would occur from P (pressure of wind), or from any stoppage in the descent throwing the gasholder out of equilibrium.

To meet the strain caused by these forces, the curb should be properly stiffened by gussets, as the top row of the side sheets and the curb row of the top sheets, being then connected, form a kind of box girder. This is more especially necessary in small holders, where the curb being formed of one or two light angle-irons they are more likely to yield than built-up girder curbs of large holders.

Having rafters and trussing to the top materially assists the curb in resisting the transverse strains. The rafters should be connected to the vertical stays by gussets. If this plan be adopted, there is little fear of the curb crippling through the tendency to buckle.

It must be noted that if the curb once starts buckling, through the wind pressure or any other cause, the strain on the curb from the top sheets being thrown out of equilibrium, it will immediately assist the buckling.

But we may conclude that the curb, if made strong enough to resist the compressive strain, is also strong enough to resist the buckling strain when made as above directed.

Compression.

Before we can determine the actual compression on the top curb, we must know the magnitude of each of the component forces—viz., S, P, W, and F.

I. To find the pull of the top sheets S.

1. Find the area of the top; D being the diameter (in feet).

2. Multiply by the pressure of gas in pounds per square foot, less the weight of one square foot of top sheeting. This will give the total *effective* pressure of gas in a vertical direction. Call it p.

3. Divide by the circumference of the holder (in feet). This will give the *vertical* strain on the curb for one foot of length, and must be resolved in the direction of a

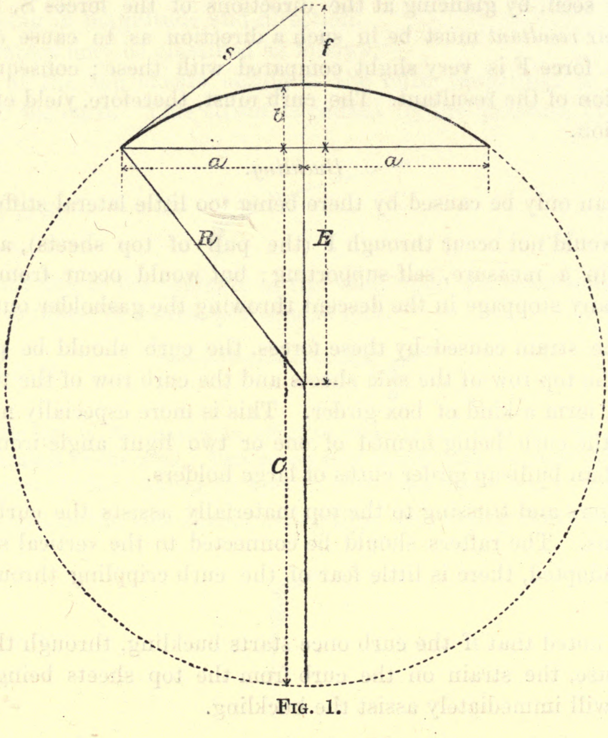


Fig. 1.

tangent to the arc at that point. We will call its vertical equivalent f. We can resolve the force graphically or mathematically.

Graphically.—Draw a tangent at the curb to the arc, cutting a perpendicular erected on the line $a\ a$, say at the centre.

Then if this perpendicular represents to a certain scale the vertical force f, the tangent s to the *same* scale will represent the pull both in magnitude and direction of the top sheets for one foot of circumference. (See exaggerated diagram—fig. 1.)

Note.—It is not necessary that the perpendicular f be drawn at the *centre* as shown, because it will be seen at a glance that it may be put at any distance from the curb, and it will not affect the ratio between it and s, as it forms a series of similar triangles. The centre is selected because it is more advantageous in working the mathematical method.

To prove that s really represents the strain due to f, it is only necessary to consider diagram (fig. 2):—

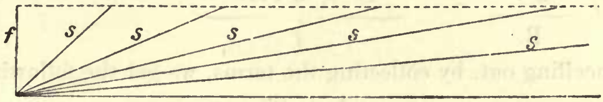


FIG. 2.

As the sheeting becomes flatter and flatter, the strain increases; f in the diagram represents the vertical force, and the increase of strain is shown by the magnitude of the line s increasing as the angle of the sheeting decreases, until it becomes theoretically infinite when the sheeting is *quite* flat. (For observations on flat-tops, see end of this paper.)

Mathematically.—But as it would be inconvenient to draw the arc and tangent correctly to scale for such large dimensions, the following method will be found preferable :—

We want to find the length s. Now as s is a tangent to the arc, a line drawn from its point of contact to its centre must be at right angles to it, and is one of the radii of the top (Euclid III. 18),

The formula for obtaining R is $\frac{a^2 + b_2}{2b}$. (See fig. 1 on preceding page.)

The proof of this formula is as follows :—

Required to prove that $\frac{a^2 + b^2}{2b} = \mathrm{R}$

$$a \times a = b \times c. \quad \text{(Eu. III. 35.)}$$

$$\therefore \frac{a \times a}{b} = c.$$

$$\text{but } \frac{c + b}{2} = \mathrm{R}. \quad \text{(Eu. I. def. 15.)}$$

$$\therefore \frac{\frac{a \times a}{b} + b}{2} = \mathrm{R}$$

$$\text{i.e., } \frac{a^2 + b^2}{2\,b} = \mathrm{R}. \quad \text{Q. E. D}$$

Now we can prove that the $\Delta\, s\, a\, f$ is similar to the $\Delta\, a$ R E. (Eu. VI. 8.)

$$\therefore \text{ the side } a \text{ in } \Delta\, a \text{ R E} : f \text{ in } \Delta\, s\, a\, f$$
$$\text{as the side R in } \Delta\, a \text{ R E} : s \text{ in } \Delta\, s\, a\, f$$
$$\text{or } a : f :: \text{R} : s$$
$$\therefore s = \frac{f \times \text{R}}{a}$$

Or, writing it in words : The radius of the top (R) multiplied by the vertical press per foot of circumference (f); and divided by half the diameter of the holder (a), will equal the actual tangential pull per foot (in pounds). Or the whole process may be stated thus, filling in the values of R, f, and a—

$$\underbrace{\frac{a^2 + b^2}{2\,b}}_{\text{R}} \times \underbrace{\frac{\text{D} \times \text{D} \times \cdot 7854 \times p}{\text{D} \times 3 \cdot 1416}}_{f} \times \frac{1}{a} = s$$

So that after cancelling out, by collecting the terms, we get the following result :—

$$\frac{(a^2 + b^2)\, p}{4\, b} = s$$

Check Proof.—A common rule to find the strain on a sphere, or segment of a sphere, subject to internal pressure is as follows :—

Multiply the pressure per square foot by the area of a "great circle" of the sphere, and divide by the circumference of same. This will give the strain per foot.

Let d = diameter of sphere; then $\dfrac{p \times d \times d \times \cdot 7854}{d \times 3 \cdot 1416} = \dfrac{p \times d}{4}$

$$i.e., \quad \frac{p + \overbrace{\frac{a^2 + b^2}{2\,b} \times 2}^{\text{diam. of sphere}}}{4} = \frac{p \times (a^2 + b^2)}{4b} = s$$

This, it will be seen, gives precisely the same result as found by the other method. The reason the other method was chosen in preference was because this plan does not show why the strain in the segment of a sphere is equal to that in the entire sphere ; but the other method proves it to be so.

This result must be multiplied by the diameter of the holder, to give the total pull right across from side to side, and divided by 2 to give the strain on one side.

The formula then stands thus—

$$\frac{(a^2 + b^2)\, p\, \text{D}}{8\, b} = s$$

Another rule giving practically the same result is $18 \cdot 3\, \dfrac{\text{W}}{a} = s$.

where W = the weight of the sides in tons, and a = the angle of the top in degrees. (See "King's Treatise on Coal Gas.")

II. Pressure of wind. P $\longrightarrow$

Pressure per square foot = 26 lbs.

Surface considered as acted upon by wind = the diameter of the holder multiplied by half the depth of the inner lift.

Half the depth is taken because the pressure on the lower half is transmitted to the columns—not by the top curb, but by the cups or bottom curb, as the case may be.

$$26 \times D \times \frac{d}{2} = 13\,D\,d$$

But as this must be divided between the two sides of the curb diametrically opposite, we must halve it. Then—

$$6{\cdot}5\,D\,d = P$$

III. Weight of sides. W.

$$\downarrow$$

Let w = the weight of the sides (total) in *pounds*—this is, of course, equal to the *effective* pressure of the gas per square foot multiplied by the area of the top. If w be divided by the circumference, it will give the weight per foot, and is = to f (the vertical equivalent of s per foot of circumference). This multiplied by the diameter, and divided by 2, will give the actual strain due to the weight of the sides.

$$= \frac{w \times D}{D \times 3{\cdot}1416 \times 2} = \text{say}\ \frac{w}{6{\cdot}3} = W$$

IV. The pressure of gas on the sides. F. $\longleftarrow$

How much to allow for this, is a matter of conjecture. Perhaps 1-5th of the total tension on the side sheets (of the inner lift only) would do for stays riveted or bolted to the sides, and 1-8th for *loose* sheets—certainly not *more* than this. For if we take a thin cylinder and subject it to external forces acting only at the top and bottom edges, we find that the upper and lower portions of the cylinder may suffer great deformation without making a very appreciable difference in the body or centre part.

The total tension on the side = $p_1 \times D \times d$. Divide this by the constant, and halve it for the two sides.

$$= \frac{p_1 \times D \times d}{10} \text{ for vertical stays attached, and}$$

$$\frac{p_1 \times D \times d}{16} \text{ for stays attached only at top and bottom}$$

p_1 = *actual* pressure of gas per square foot.

Having determined the magnitudes of these four forces—viz., S, P, W F—we must next investigate how their direction affects their resultant.

Proceed as follows:—Draw diagram for finding the resultant of S and W parallelogram of forces).

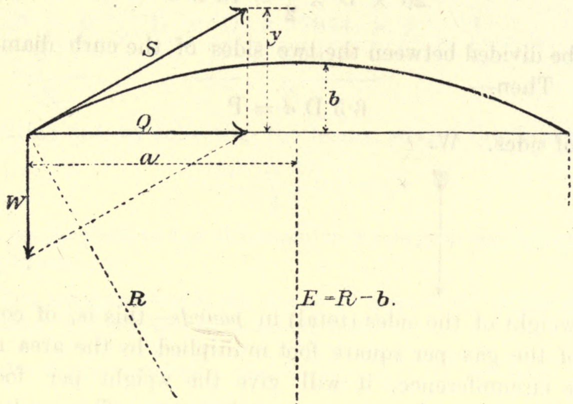


FIG. 3.

It will be found upon consideration that the resultant Q *must be horizontal.* (1) Because the vertical equivalent of S is equal to W; and (2) should the resultant Q not be horizontal, but inclined upwards, then the gasholder would always be moving upwards, and if down, then downwards. But this cannot be, as the forces and resistances at the point of application *must* be in equilibrium.

Referring to the above diagram, the $\triangle$ Q S y is similar to the $\triangle$ a R E; and the $\angle$ R E is equal to the $\angle$ S Q.

$$\therefore \ R : S :: E : Q$$

$$i.e., \ \frac{S \times (R - b)}{R} = Q$$

Having found Q, the resultant of the remaining forces P and F is easily found both being horizontal.

It will be equal to their difference: viz., P − F.

Adding this resultant to Q, the resultant of all the forces will be: Q + P − F.

Now filling in the values of Q, P, and F, we get—

$$\frac{S \times (R - b)}{R} + 6{\cdot}5\,D\,d - \frac{p_1 \times D \times d}{c}$$

$$c = \text{constant, 10 or 16.}$$

Inserting the values of S and R, we get—

$$\frac{(a^2 + b^2)\,p\,D \times \left(\frac{a^2 + b^2}{2\,b} - b\right)}{8b \times \frac{a^2 + b^2}{2b}} + 6{\cdot}5\,D\,d - \frac{p_1\,D\,d}{c}$$

$$= \frac{(a^2 + b^2)\,p\,D \times \left(\frac{a^2 + b^2}{2b} - b\right) \times 2\,b}{8\,b \times (a^2 + b^2)} + 6{\cdot}5\,D\,d - \frac{p_1\,D\,d}{c}$$

$$= \frac{\left(\frac{a^2 + b^2}{2\,b} - b\right) p\,D}{4} + 6{\cdot}5\,D\,d - \frac{p_1\,D\,d}{c}$$

This may be expressed, in a very simple form, as follows:—

$$\underbrace{\frac{(a^2 - b^2)\,p\,D}{8\,b}}_{Q} + \underbrace{6{\cdot}5\,D\,d}_{P} - \underbrace{\frac{p_1\,D\,d}{c}}_{F} = x$$

which is the exact formula required, where—

a = half the diameter of holder (*in feet*)
b = rise of crown ,, ,,
D = diameter of holder ,, ,,
d = depth of inner lift ,, ,,
p = effective pressure of gas (pounds per square foot)
p_1 = actual ,, ,, ,, ,,
c = 10 for vertical stays fastened all the way up
c = 16 ,, ,, loose
x = compression on one side of the curb in pounds (total) where there is *no trussing to top.*

p may be found thus: Deduct the total weight of the top sheets from the total weight of the gasholder (floating) in pounds, and divide the difference by the area of the top in *square feet.*

p_1 may be found by merely dividing the total weight of the gasholder (in pounds) by the area of the top (in square feet).

Writing the foregoing formula in words, it may be expressed as follows, keeping in mind that all lineal dimensions are in feet:—

From the square of *half the diameter* of the holder deduct the *square* of the *rise;* multiply the difference by the effective pressure of the gas (p) and by the *diameter* of the holder; divide this result by 8 times the *rise,* and to the quotient add 6·5 times the depth of the inner lift, multiplied by the diameter of the holder.

From this result must be subtracted 1-10th or 1-16th (as the case may be) of the diameter of the holder multiplied by the depth and by the *actual* pressure of the gas (p_1). This difference will give the compressive strain required.

A rule given by Rankine for finding the portion of formula represented by Q may be expressed as follows:—

$$\tfrac{1}{2}\, p\, a \sqrt{\left(\frac{a^2 + b^2}{2\, b}\right)^2 - a^2} = Q$$

This gives precisely the same result, but it is not expressed in so simple a form.

It is very difficult to determine how much of the gasholder sheeting should be included in the top curb in apportioning the sectional area.

It has been said that the whole of the top sheets right across the top are in compression. This appears to be an error; for, supposing the top to be *cut across* the centre, it seems highly probable that instead of the two halves *closing together* with compressive force, they would open apart, the gap being the largest in the centre and gradually diminishing till it gets near to the curb, when the point will be arrived at where compression commences, and then gradually increases in intensity as it approaches the angle of the curb.

Any hollow vessel subjected to an internal pressure *tends* to become a sphere. Applying this to the gasholder—

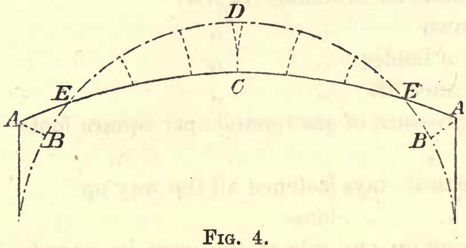


Fig. 4.

the corners A tend to draw into B, whereas C flies out, stretching itself more or less towards D, there being a kind of neutral circle, previous to the deformation, somewhere about E.

Again, I do not think the "egg ends" of boilers are ever supposed to be in *compression right across;* and the case is analogous.

Perhaps a fair allowance to make is to assume the two outer rows of the top and

the top row sides as forming part of the curb in the strong plate curbs of large holders of good design.

The joints in these plates should be *butted*, when the full sectional area of plate may be considered as effective. If they are *lapped*, the strength will be very little more than the shearing strength of the rivets.

Lap joints are quite sufficient for small holders or large ones having *trussed* tops.

NOTES.

If the holder is in a house, omit 6·5 D *d*. from the formula.

In gasholders which have a series of trussed rafters springing from the centre of the holder, and well connected to the top curb, a considerable allowance may be made for the trussing—Firstly, because the rafters prevent the top drawing the top curb in by the direct thrust which they have upon the curb, in the same manner that the spokes of a wheel prevent the collapse of the rim. Secondly, under the action of the wind the curb has many points of support.

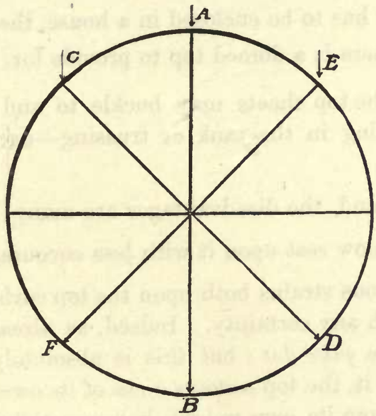


FIG. 5.

In the above sketch the thrust caused by the wind acting at A is communicated in a measure to the opposite column at B by the rafters. The force at C is partly in a direction tangential to the curb, and partly transmitted by the rafters to the column D; and the same with the force E to F.

Thirdly, the purlins or bracket bars assist by preventing the bending of the rafters sideways. The outer one should be made strong, as it acts somewhat similarly to the inner angle-iron ring of some top curbs.

In trussed-top holders from $\frac{1}{4}$ to $\frac{1}{2}$ of x may be taken as the actual strain upon the curb, according to design, &c.

Holders having a series of girders arranged both radially and in circles, to which the top sheets are *riveted*, have the top curb very light. Indeed a different process altogether must be adopted for finding the strain upon it; and consequently the foregoing formula will scarcely apply.

The Fulham, Kensal Green, and Shoreditch gasholders (erected by C. & W. Walker) furnish excellent examples of this kind of holder.

Flat-top Gasholders.

There appear to be very few advantages in adoping this kind of holder.

1. There is less waste of gas when the man-lids have to be taken off to examine the interior, owing to the top being practically level with the water when the gasholder is at rest.

2. When the holder has to be enclosed in a house, the building may possibly be of less height than when there is a domed top to provide for.

3. Admitting that the top sheets may buckle to and fro, they will carry themselves without any framing in the tank or trussing—except, perhaps, a post in the centre.

But, on the other hand, the disadvantages are many.

1. The water and snow rest upon it with less encouragement to flow off.

2. There are enormous strains both upon the top curb and the sheeting; and they cannot be calculated with any certainty. Indeed, as already stated, the strain would be infinite if the top were *quite flat;* but this is absolutely impossible, for as soon as the pressure comes upon it, the top *assumes a rise* of its own accord, in the same manner as a long wire will sag from its own weight, however tightly it may be stretched. Of course this rise depends upon the looseness of the sheets; the looser they are, the greater the rise and the less the strain. In working out the strain on curb, a *rise* must be assumed, and the formula applied to find the strain.

3. Owing to the great strain, and the alternate rising and falling of the sheets, the joints must be racked a great deal, weakened, and very liable to leak.

4. All this wear and tear, added to the first cost, must necessarily make this class of top very expensive.

In conclusion, it may not be out of place to give the two following rules relating to the joints in top sheets :—

I. To find the *shearing* strain on the rivets in the top sheets *per foot lineal*—

$$\frac{(a^2 + b^2)\, p}{4\, b} = \text{strain required.}$$

II. To find the thickness of the crown sheets, allowing the safe tensile strain to be 5 *tons per square inch of section*—

$$\frac{(a^2 + b^2)\, p}{5376\, b\, \mathrm{P}} = \text{thickness in parts of an inch.}$$

P is the percentage which the strength of joint bears to the solid plate (see Molesworth) ; the other factors as before explained.

With regard to the second rule, other considerations besides merely resisting the *strain* upon the sheets influence the determination of the thickness—such as wear and tear, oxidation, sound joints, riveting to thick plates, &c., &c. ; so that in most cases it becomes necessary in practice to increase the thickness beyond that given in the formula ; but the formula provides for the *actual strain* upon them.

GASHOLDER CROWNS.

[Reprinted from the Transactions of The Gas Institute for 1884.]

GASHOLDER crowns are of two kinds—viz., those which have the crown sheets supported by a trussed frame rising and falling with the gasholder, commonly known as "Trussed Tops," and those which have no trussing in the crown, but are supported by a separate wooden or iron frame fixed in the tank.

The present paper will be divided under three heads—

I. The comparison of the two kinds of crowns above mentioned—viz., trussed and untrussed tops.

II. The consideration of some important points of detail in connection with trussed tops.

III. The determination of the true form of curve for gasholder tops.

I. With regard to the first division of my subject, it is easy to show that the advantage of an untrussed top is greater in a large gasholder than in a small one; for the separate frame built in the tank does not require to be much stronger, however large the gasholder may be made. In other words, the framing for carrying a 200-feet top need not be any stronger, area for area, than for a 100-feet top; the only difference being that there is four times as much surface to support. But with a trussed top a 200-feet gasholder not only requires four times as much area of trussing as a 100-feet holder, but (owing to the increase of span) it must also be made of much stronger sections in order to carry itself. It is, therefore, much heavier in proportion. It follows, then, that there must be a limit beyond which it is decidedly uneconomical to adopt a trussed top; and this limit can only be defined by comparing the cost of the two plans for gasholders of the same size.

It must be borne in mind that the deeper the holder, the greater will be the cost of the fixed frame, as all the standards or uprights in the tank have to be higher. The depth, however, does not affect a trussed top to the same extent. It is also well known

that untrussed tops require a much heavier and stronger top curb. For large gasholders, such as Mr. Livesey's gigantic holder, it is undoubtedly more economical to have an untrussed crown. It would probably be so for holders as much as 50 feet less in diameter; but for how much smaller than that I am not able to say, as it depends so much upon circumstances. I cannot help thinking, however, that it would be unwise to abolish trussing in small gasholders, for it is so light that it would appear impossible to put anything cheaper into the tank in the form of a separate frame. Trussed tops are also very convenient for manufacture, as the top can be put together, and sent away from the contractor's yard so complete that he is sure of it coming together well in the erection. Not so, however, if he had to depend upon a separate framing in the tank, with which probably he has had little to do.

It has been said with reference to small holders of the untrussed type, that the weight saved from the trussing should be thrown into the perishable parts (such as the sheeting, &c.), in order to get sufficient pressure of gas. But, if this be done, what is to pay for the necessary framing in the tank? For the expense is certainly greater if the weight of the holder is to remain the same as for a trussed crown, and a frame is put in the tank *in addition*.

But, besides the advantage of being less expensive in small gasholders, trussing is of use in relieving the top curb of much strain that would otherwise come upon it. It has been said that the introduction of trussing weakens the top curb, through the extra pressure of gas causing the top sheets to pull on it with greater force. This appears to be a wrong inference; for, although there is a greater inward pull, the curb is in a better position to resist it. In fact, the strain due to the extra pull is not to be compared to the additional support, stiffness, and resistance to buckling given to the top curb by the strut action of the rafters upon it.

In relation to wind pressure, the rafters occur just where they are wanted—viz., behind the roller carriages; for the carriages thrust back upon the gasholder with the same force as they push at the columns. The rafters then return the pressure right across the holder to the opposite side; in fact, back to its origin. Again, supposing there are no rafters, the bending or buckling strain on the curb must be excessive, as it does not get any direct support, but merely from the guide framing resisting distortion of the circle, in the way pointed out by Mr. B. Baker, in his report on the strains in Mr. Livesey's large holder;* and this only effectively, when the rollers fit tightly against the guide. Or, to make it still clearer, when rafters are used (instead of the pressure from force of

* See *Journal of Gas Lighting*, Vol. XXXVII., p. 141.

wind being passed on, as it were, right round the circle to the opposite side, racking and bending the top curb on its way), it is transmitted directly across the gasholder to the opposite columns by the rafters.

I think we may conclude, then, that the assistance rendered by the trussing to the top curb is much in excess of the strains induced by the extra pressure of gas due to its weight.* This added to the other points mentioned should not be overlooked in discussing the merits and demerits of gasholders with trussed crowns.

II. I will now made a few general remarks on trussing, and then turn particular attention to (1) the main tension-rods; and (2) the advisability or otherwise of attaching the crown sheets to the framing in the centre.

The rafters are prevented from distorting or crippling side-ways by the purlins. They cannot bend downwards, as they are supported by their trussing; and, being arched upwards, they are more liable to bend in this direction under end-thrust. But the sheeting, their own weight, and the purlins combined, all tend to keep them down. When the gasholder is down—*i.e.*, at rest in the tank—the purlin bars, besides transmitting the weight of sheeting, &c., to the rafters, assist the trussing to the rafters to a certain extent; for if the trussing failed, the purlins would all be thrown into compression, like a dome, and so the top could not sink unless the purlins crushed up.

In most instances the trussing consists of a strong centre column, with a series of rafters radiating from centre to curb; each rafter being trussed independently. And

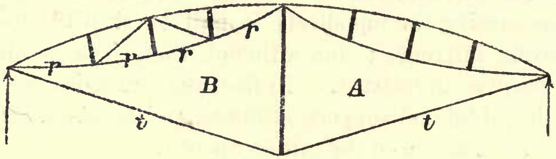


FIG. 1.

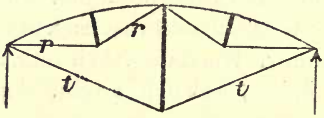


FIG. 2.

then, in addition, there are a number of very strong main tension-rods, so as to carry the weight which comes upon the centre column. Figs. 1 and 2 are examples.

* For other considerations on the subject of the top curb, and the influence of trussing, see my paper on "The Strains upon the Top Curb of a Gasholder," published in the Institute's Transactions for 1882 (also in the *Journal of Gas Lighting*, Vol. XL., p. 170). *Ante*, pp. 74 to 85.

But sometimes the main tension-rod *t* is a continuation of the rafter tie rod *r*, as in fig. 3.

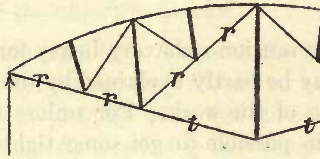


FIG. 3.

This is not so good a form for erection; it is so deep, and flimsy to handle. Besides, it cannot be sent away from the makers in such convenient pieces; and in tightening up the rods *t t* it would be possible to distort the other part of the frame, or cause the strain to be irregularly distributed.

It should be noted that in no case should a large gasholder have a truss like A (fig. 1). It is very imperfect, as it induces undue bending strains on the rafters, and is free to twist all shapes. The panels should have light ties across in the proper direction, as shown at B (fig. 1). Single ties are sufficient. There is no necessity for crossing them, unless the holder is very large, when the middle panel could have a crossed pair of light angle-irons, to give rigidity to the structure. The other panels must have the rods sloped in such directions as to form ties under the weight.

The determination of the strains on the trussing is a simple matter by Clerk-Maxwell's method, an application of which may be found in the *Journal of Gas Lighting* for July 29, 1879. Bow's system of lettering should be used; it simplifies the process. The weight or load coming upon the trussing when the holder is at rest is, under the most trying conditions, the weight of the top sheets, the weight of snow, and the weight of the trussing itself. When the gasholder is up, however, the only load upon the trussing is the last item—viz., the weight of the trussing itself.

A centre pier is generally built in the tank, for the centre column to rest upon, and deposit its load when the gasholder is down. In the paper already referred to, this was disregarded. It should, however, be taken into consideration if the gasholder has been properly constructed.

Main Tension-Rods.

When the centre column rests upon the pier, it is evident that the main tension-rods *t t* are idle; the weight of the top coming direct from the rafters on to the centre column at one end, and on to the vertical stays at the other. The truss *r r* supports the rafter between; for which purpose the rods *t t* are, of course, useless. So that it

is only when the gasholder is up that the main tension-roads are called into play; and then they take the proportion of the weight of trussing which comes upon the centre column.

It is the custom to make the main tension-rods very heavy for the work they have (or should only have) to do. This may be partly explained by the difficulty there is in getting each rod to do an equal share of the work. For unless the greatest care is taken in tightening them up, it is quite possible to get some tighter than others; and so, when the gasholder rises, the greater part of the weight of trussing may be thrown upon a few rods. Also, should the gasholder from any cause tilt, or get checked in its descent, the strain on the rods would be very excessive.

Again, in erecting the gasholder, it is frequently the practice to plate the top, having the rafters and centre column lowered slightly in the centre; and then, when the top is done, the main tension-rods are all tightened up so as to lift the centre to the proper rise, and pull all the sheets as tightly as possible over the rafters. This gives the top an excellent appearance. and frees it from hollow places, &c. It is evident, however, that this process must strain the rods very much, as the whole crown (including the weight of the sheets) has to be lifted off the centre pier. When it is adopted, therefore, it should be performed with great care, so as to get all the rods to take an equal share of the weight. It should not be done unless special provision has been made for the rafters lengthening. Otherwise the strain will be enormous, as the exaggerated diagram fig. 4 will show.

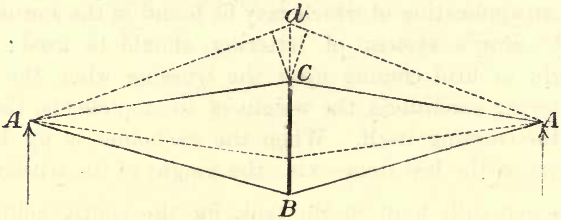


FIG. 4.

A A B C represents the original position of the frame. On lifting the centre from C to *d*, it is clear that the line A C must extend to A *d*, as shown by the dotted line. It certainly seems a pity to make the rods excessively strong merely to meet the strains incurred during the erection, and which should never occur again after the holder is put to work. Instead of lifting the centre by means of the main tension-rods, it would be far preferable to use jacks for the purpose, or employ any other means that will avoid straining the rods. Before releasing it, the centre pier should be made up to the full

height, so that the centre column actually bears upon it. The main tension-rods can then be tightened up gently—not so as to lift the column off the pier, or the pier is rendered useless, and the object frustrated.

Particular attention should be given to the end attachments of the main rafters. After the centre has been lifted, they should be most rigidly fixed, so as to avoid any possibility of slipping or yielding when the gasholder is lifted by the gas. Unless these end joints are firm, the rafters not only lose much of their power to transmit the thrust across the gasholder, but both the top curb and the main tension-rods are strained more than they need be.

Strain on Main Tension-Rods.

When the framing is constructed and erected in the manner recommended, it is a most simple matter to find the strain on the main tension-rods.

Let A B C D (fig. 5) represent the frame.

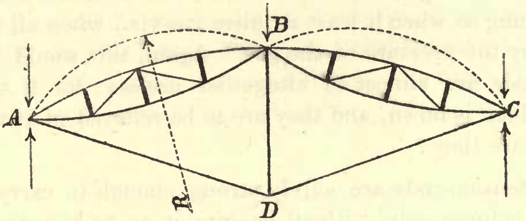


FIG. 5.

The trussing to the rafters A B and B C is quite independent of, and therefore does not affect in the slightest degree the strain on the main tension-rods A D and D C. Now it can be proved that if B D represent, to a certain scale, the weight coming on the centre, then the length of the line A D, to the same scale, is the actual strain upon the rod; and this is true for any rise or angle. The only condition is that no joint must yield or slip.

Nothing could be simpler that the following rule, which results from the above:—Multiply the central weight at B by the length of A D; and divide the product by the length of B D. The result will be the actual strain upon the main tension-rods. The weight B is important. We shall be erring on the safe side if we take it as equal to half the weight of the entire top framing and trussing (the top curb and sheeting must not be included). This is, of course, for all the rods, and must be divided by the number of rods to find the strain on one. In the figure there are two rods—viz., A D and D C. If the rods are designed to take 3 tons per square inch strain under the

above load, there will be a sufficient margin left for ordinary casualties, unequal tightening up, corrosion, &c.

It is scarcely needful to mention that the screwed ends of the rods should be larger in diameter than the plain part, unless they are for a very small holder; and that long heavy rods should have suspenders to take the sag out, and make them direct. A main tension-rod should, if possible, be put at each main rafter, and be of light section, in preference to a few rods of heavy section. This will maintain uniformity of pressure on the top curb from the rafters.

Attachment of Sheeting in the Centre of the Crown.

It is frequently the practice to fasten the sheets down, in the centre of the crown, to the centre column. This is done with the idea that it aids either the trussing or the sheeting, or both. The fact is, it is of very little good to either; but rather the reverse, as the following will show. When the gasholder is down, it does not affect either the trussing or sheeting in any way whatever; and when it is up, if it be to support the trussing, it is doing so when it least requires it—viz., when all the superincumbent weight is lifted off by the pressure of the gas. Again, this would make it appear that the main tension-rods are almost or altogether useless; for if they do not get any strain when the holder is down, and they are to be relieved of it whenever the holder is up, of what good are they?

But the main tension-rods are surely strong enough to carry the weight of the trussing and centre column only, without hanging it on to the sheeting in the centre. It may be worthy of remark that the main tie to the rafter truss is always made less than the main tension-rod, although it frequently has more work to do.

If the sheets are made to take the weight at the centre, they are bound to sag inwards, and form a concavity in the centre of the top; for, under pressure, the top sheeting stretches, and is lifted off the framing, except at those places where it is held down. (See exaggerated diagram fig. 5.) This is most undesirable, as it holds the water and looks very ugly. To avoid this depression in the centre, the best gasholder makers flatten the curve between the curb and centre, as in fig. 6.

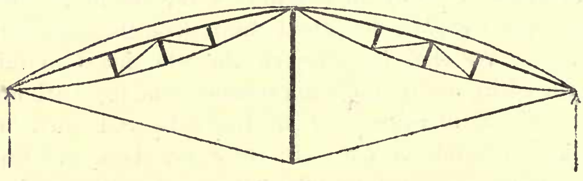


FIG. 6.

The rafters being bent to the flatter curve, and the sheeting drawn tightly over them, it is evident that when the pressure of gas comes upon them they balloon out on each side of the centre, and take up something like the curve intended. The amount of flattening that is required is determined from experience; and so the depression or concavity in the centre is avoided. On the other hand, if the attachment of the sheets in the centre is to strengthen the sheets themselves, it can easily be shown that they do not need it; and more than this, it is impossible for them to obtain assistance from this source if they do, unless with the top shown in fig. 5.

When the top sheets are loose, the centre part and all rises from the framing, under pressure due to the stretching of the sheeting. This diminishes the diameter of the sphere, of which the top is for all intents and purposes a segment; and so reduces in proportion the strain upon the sheets. If, however, the centre is held down, but no flattening has been put in the curve, the curved arc (fig. 5), having a smaller radius still (R) than the radius of the sphere for the loose top, would have less tension upon it. But if the rafters, &c., be flattened—which should always be the case with tops having sheets fixed in the centre—the resultant arc, when the pressure of gas comes upon the top, must have a larger radius than that of the arc due to the loose top entirely.

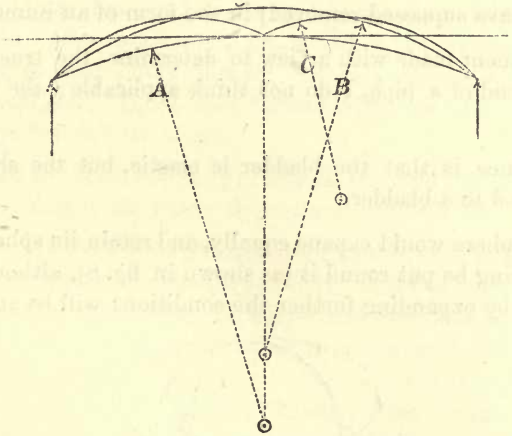


FIG. 7.

This is very easily proved. If there be no depression, the strongest arc for fixed sheeting must be tangent to a horizontal line at the centre, as at A in fig. 7, which also shows each of the arcs under different conditions:—A being the curve for the

fixed centre, with no depression; B, the curve for the loose top entirely; and C, the curve for the fixed centre and hollow.

Therefore, unless we adopt the hollow, ugly, dented top, we are forced to the conclusion that attaching the sheets at the centre not only does not help them to resist the strains upon them, but is not so strong as when they are quite loose, and free to rise throughout. Neither does it do any good to the trussing, which is self-supporting.

III. I will now pass on to the third division of my subject. Time, however, forbids my giving more than the bare results of my investigations with respect to the true curve for gasholder tops. (See Note A, p. 96.) They are as follows:—That if the sheeting is to be subject to uniform strain throughout, the top must be the segment of a sphere, and is therefore in section the arc of a circle. It can be proved thus—

1. Suppose the entire sphere of which the top forms a part is subjected to internal pressure, no one would contend it is not uniformly strained; it being well known that a sphere is the only vessel which has uniform strain throughout.

2. Providing the sphere is non-elastic, if we slice off a segment and fix its outer edge (such as we do in the gasholder top by the top curb), the conditions of strain remain unaltered; for we are merely providing a substitute for the lower portion of the sphere (which we have supposed removed) in the form of an immovable ring.

3. The experiment made with a view to determine the true curve by stretching a bladder over the end of a pipe, I do not think applicable; the conditions not being the same.

4. The difference is that the bladder is elastic, but the sheets are practically inelastic as compared to a bladder.

5. An elastic sphere would expand equally, and retain its spherical form under any pressure; but if a ring be put round it (as shown in fig. 8), although on just touching, the strain is equal, by expanding further the conditions will be at once altered. The

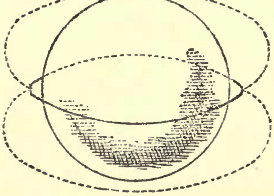


Fig. 8.

material will be gathered in and prevented from expanding at the ring, in the same way as the pipe prevents the bladder expanding round the circumference ; and as the expansion continues, the shape will become more and more remote from that of a sphere, as is shown by the dotted lines.

6. Similar reasoning applies to the segment of an elastic sphere. It is merely putting the ring higher up—say at *a*, in fig. 9.

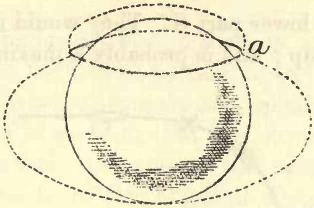


FIG. 9.

7. Not so with iron sheeting. The pressure is insufficient to cause much expansion from the original shape ; and so, the segment remaining practically of the same size and form, the strains remain uniform as before.

8. But suppose the tops of gasholders were made the shape it is supposed that they would take under pressure, the result would be that when the pressure came upon them, they would stretch just as much, only they would take a shape a step further removed from the segment of a sphere. But I have before stated that the segment of a sphere is the only perfect shape for uniform strain.

9. If we must allow for the stretching of sheets, it would seem almost necessary to flatten, instead of bulging them, where they spring from the curb.

There is one point, however, which is deserving of mention, and which would tend to modify the foregoing remarks in some degree—viz., that the outer row of top sheets is often considered as forming part of the top curb ; and that, therefore these sheets are in compression. This is so only when the top curb is unable to offer the whole of the resistance required. The slightest contraction to strain of the top curb is immediately taken up by the curb row of plates. But it is evident, from former remarks, that if the ring to which this row of plates is attached be perfectly rigid and unyielding, it would be impossible for the plates to be in compression ; they would have an equal tensile strain throughout, in all directions.

The effect, so far as I can judge, of making the curve of the shape as shown in

fig. 10 is to extend the compression a little further up the curve, which may or may not be an advantage. Wyatt's curbs (fig. 11) serve to illustrate this view. We might put

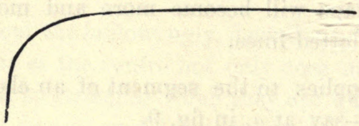


FIG. 10.

many angle-irons, &c., at the lower part S. They would do little good. The resistance nearly all takes place higher up ; and is probably a maximum at about the part marked by a × in fig. 11.

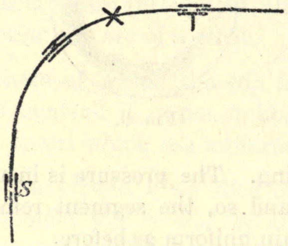


FIG. 11.

But if we want uniform strain upon the top sheets throughout, there is only one curve that will give it—the arc of a circle.

The strain per lineal foot on a joint, taken anywhere and in any direction, is given by the formula—

$$\frac{(a^2 + b^2)\,p}{4b} = \text{strain in lbs.}\quad \text{(See Note B, p. 97).}$$

Where a = half the diameter of the holder in feet.
b = rise of the crown in feet.
p = pressure of gas in pounds per square foot—effective.

If the curb row of sheets are called upon to do duty for the top curb, they must be thicker. (See my paper on "Top Curbs," already referred to.)

In conclusion, it is worth while bearing in mind that the strain is the same for any diameter gasholder crown, providing they are all made to the same curve (that is, segments of the same sphere), and that the pressure of gas is the same.

NOTE A.

What I mean by the "true curve" for gasholder tops is that curve which will, when the pressure comes upon it, give *an equal strain throughout the top*.

If it were not for the sheeting *stretching*, the segment of a sphere would undoubtedly be the proper and only correct shape to satisfy this condition. The segment of a sphere is the *only* shape which will possess uniform strain both in magnitude and character in all directions. Therefore, if we want to allow for the stretch of sheeting, or, in other words, the *elasticity* of the iron, we must make the top of such a form that it will, *after it has stretched*, be the segment of a sphere. This, however is too great a nicety, and scarcely practicable. On this ground, therefore, I say that the segment of a sphere is the true curve.

Now, in the *bladder* experiment, we find that, on account of the puckering up to the edge, and the stretching of the middle portion, when the bladder is tied over the end of a pipe, the curve assumed is not a segment of a sphere—it is somewhat like a semi-ellipse. But are we therefore to conclude that it is strained *uniformly in all directions?* I think not. Nor can we conclude that this is the proper curve for gasholder tops; because if a gasholder were made to the elliptical curve, as soon as the strain comes upon it it would *stretch*, and so would take up *another* curve. We ought therefore to say that this latter is the "true curve" to which the top should have been made. But it is not; for if we made the curve so, it would, as soon as it was stretched under strain, take up another curve directly, and so we might go on *ad infinitum*.

We must therefore conclude that, if we want to be exact, we must make the top of such curve that *after* it has stretched it will become the *segment of a sphere*. This, however, is quite unnecessary, as the stretching of the iron is so little that if the top be made the segment of a sphere, it practically remains so after the strain comes upon it.

Note B.

It is, I think, very generally believed that the strain on the top sheeting of a gasholder varies inversely as the rise of the crown; but this is not quite correct, as the following will show:—

1. It is easily proved that the strain varies *directly* as the radius of the sphere of which the top is a segment. (This is proved in my paper on "Top Curbs.")
2. It can be proved that when the rise of a (see diagram on next page) is half of b, the radius of a cannot be double of b.

Thus: Let $a = 10$
$b = 20$
$c = 30$

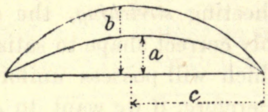


FIG. 12.

Then, by the ordinary rule, the radius for the rise b is—

$$\frac{b^2 + c^2}{2b} = \frac{400 + 900}{40} = 32\tfrac{1}{2}.$$

And the radius for the rise a is—

$$\frac{a^2 + c^2}{2a} = \frac{100 + 900}{20} = 50;$$

which, of course, is not double of $32\frac{1}{2}$.

3. The strain on the one cannot thus be double the strain on the other.

The generally received opinion, that the strain varies inversely as the rise, is therefore incorrect.

For flat arcs, such as are used for gasholder crowns, it is so very approximate that it may be taken as correct.

The following may be noted :—

I. The strain varies directly as the diameter or radius of the sphere of which the top is a segment; and as the pressure of the gas.

II. From this it follows that all gasholders whose tops are segments of the same sphere have equal strain; providing the pressure of the gas and thickness of sheets is the same.

III. All gasholder tops can be made of the same curve; and, unless the pressure varies, the same thickness of sheets would do for all size tops. The pressure would then govern the thickness of sheets.

IV. The strain is the same in all directions—rings and radial seams alike.

(*Note.*—There are other reasons for making the curb rows stouter. See paper on "Top Curbs," and V.)

V. The strain is tensile throughout, unless they are called upon to do duty for the top curb.

VI. My rules for strain on sheeting, given in the paper on "Top Curbs," can be proved to be absolutely correct.

VII. The old rule—that the "rise" of the crown should be 1-20th of the diameter—is altogether incorrect; there not being the slightest foundation for it, either scientifically or practically. [In a discussion which followed the reading of the foregoing paper, Mr. George Livesey fully exposed the absurdity of the old rule for the rise of a gasholder crown.]

STRAINS ON LARGE PURIFIERS.

It will be convenient to consider the strains in the following order, which will divide the paper into three parts—viz.:

I.—The strains on the bottom plates.

II.—The strains on the side plates.

III.—The strains on the top, or cover.

PART I.—THE STRAINS ON THE BOTTOM PLATES.

At first sight it might appear that there cannot be very much strain upon the bottom of the purifier, taken as a whole, as it is solidly bedded upon a firm foundation. But, upon consideration, we shall find that it is far otherwise; and it may happen, indeed, that the bottom plates are strained very much beyond any other part of the structure, unless some special means have been adopted of meeting and counteracting the forces acting upon them. If we take an air-tight box, made of some light and tolerably elastic material (such as paper), and subject it to a great internal pressure, we shall notice that the sides, the top, and the bottom would all bulge or balloon out, owing to their inability to withstand the strain upon them as *flat* surfaces. Also supposing the box to be resting upon a flat surface, we should find that the weight of the sides would be insufficient to prevent the bulging of the bottom; and consequently the sides of the box would be lifted completely off the table, and it would, as it were, sway or roll about, being poised on the centre portion of the bottom. In other words, its merely resting or standing upon a firm and level foundation is no protection against the bottom bulging out, and so lifting the sides. This bulging is, of course, due to the fact that any hollow vessel subject to internal pressure tends to become a sphere.

Now, a purifier is exactly analagous to the case cited. It is, comparatively speaking, a thin box; and its sides, its top or cover, and its bottom have likewise a *tendency* to bulge out when subject to the pressure of the gas from within. In the case of small purifiers, we shall find that the tendency for the sides to lift is met entirely by the weight of the sides themselves. But in very large ones, it is not so; for the weight of the sides does not increase in the same proportion as the area of the purifier is increased. It is evident that the bottom plates are not stiff enough in themselves to resist bulging downwards. They have, it is true, a series of little shallow girders, in the form of flanges; but they are quite unequal to any excessive bending strain. Consequently, they are unable to transmit the entire, or any great proportion of the downward pressure of the gas, to the outer edge. Therefore, unless the weight of the side plates, &c., is sufficient to balance the upward pull of the cover, it is quite possible that the excess is more than the bottom plates are capable of resisting.

The lifting forces acting vertically upwards are—

1. *The Buoyancy of the Gas.*

This is equal to the difference of the total weight of gas in the purifier and the air displaced. A purifier 40 feet square by 7 feet mean depth would contain 11,200 cubic feet of gas. The excess weight of 1 cubic foot of air over 1 cubic foot of gas at (say) 36 inches pressure equals (say) 0·04 lb.; therefore the lifting force due to buoyancy is $11{,}200 \times 0{\cdot}04 = 448$ lbs., or 4 cwt. This is a mere trifle; and therefore the buoyancy may be disregarded altogether.

2. *The Lifting due to the Upward Pressure of the Gas.*

The total maximum lifting pressure in *tons* is equal to the area of the purifier in *square feet* multiplied by the depth of the lute in *inches* and by the constant 0·00233.

Notes.—The area of the purifier (not the cover) is taken, because the pressure of gas downwards in the lute (inside the cover) exactly balances the upward pressure on the part of the cover immediately above it.

The depth of the lute is sometimes greater on the outside than on the inside; in which case the greater depth must be taken.

0·00233 is the weight in tons of 1 sq. foot of water 1 inch deep.

This, then, may be considered as the only force tending to lift the sides, and through them the bottom plates.

The resistance to this lifting may be enumerated as follows:—

(1) *As much of the downward pressure of the gas on the bottom plates, added to the weight of the plates themselves, as the bottom plates will transmit, without undue strain upon them and bending.*

To determine this exactly would be almost impossible, and quite unnecessary, as it can be solved very approximately in the following way:—Suppose the pressure per square foot is given, it is required to find the extreme length a cantilever can be made when subject to a uniform load of so much per foot of length, and having a depth equal to the thickness of the bottom plate, and a breadth equal to the width (say 60 inches), and not to be strained beyond (say) one-sixth of the breaking weight. Allowance must be made for the flanges, by treating them as cantilevers, and combining them with the plate as shown below, which is sufficiently accurate for all useful purposes.

The formula for a safe load on a cantilever under the above conditions is—

$$W = \frac{2\ K\ B\ D^2}{6\ L}$$

where W = safe load in hundredweights = one-sixth of the breaking weight; or

$d \times 0{\cdot}232 \times \frac{L}{12,}$ where d = depth of lute in inches.

K = constant, 46 for cast iron.

B = breadth, say 60 inches (ordinary size).

D = thickness of plate, $\frac{5}{8}$ or $\frac{3}{4}$ inch.

L = length required in *inches*; or, in other words, the extreme width of margin all round the bottom plates, upon which the gas acts effectively in keeping the sides down.

For strength of flanges, $b = 1\frac{1}{2}$ inches; $d = 3$ inches (average size).

Then inserting the values in the formula, we get—

$$\begin{array}{ccc} & \text{Plate.} & & \text{Flange.} \\ W = & \dfrac{92 \times 60 \times \frac{5}{8}^2}{6 \times L} & + & \dfrac{92 \times 1{\cdot}5 \times 3^2}{6 \times L} \end{array}$$

$$\therefore W = \frac{360}{L} + \frac{207}{L} = \frac{567}{L}$$

$$i.e., d \times 0{\cdot}232 \times \frac{L}{12} = \frac{567}{L}$$

$$\therefore L = \sqrt{\frac{567 \times 12}{d \times 0{\cdot}232}} = \frac{172}{\sqrt{d}}$$ for $\frac{5}{8}$-inch thick plates; and, by a similar process, $L = \dfrac{194}{\sqrt{d}}$ for $\frac{3}{4}$-inch thick plates.

The following table gives the distances L for pressures between 18 and 36 inches, and for bottom plates $\frac{5}{8}$ or $\frac{3}{4}$ inch thick. For convenience, L is given in *feet* :—

Depth of Lute, in Inches.	L for $\frac{5}{8}$-inch Plates.	L for $\frac{3}{4}$-inch Plates.
18	3·37	3·81
21	3·12	3·53
24	2·93	3·30
27	2·76	3·11
30	2·63	2·96
33	2·50	2·81
36	2·38	2·70

The resistance to lifting by the pressure of gas on the bottom plates is then obtained by multiplying together the factor L obtained from the above table, the length round the purifier (in feet), the depth of the lute (in inches), and the constant 0·00233. All the rest of the pressure of gas on the bottom plates is useless for resisting the lifting of the sides, as the plates are not strong enough to transmit it.

(2) *The Total Weight of the Side Plates* (*in tons*).

This is, of course, very easy to obtain when the section of the side plate is known; but, as a very rough guide for immediate use, the following table may be sufficient :—

Rule—Multiply the length round the purifier by the weight per foot in hundred weights (given in the table), and divide by 20, to bring into tons.

Depth of Purifier, in Feet.	Depth of Lute, in Feet.	Weight per Foot, in Cwts.
4½	2	1·75
5	2	2·00
5	2½	2·10
6	2½	2·60
6	3	3·00

Note.—The above weights include flanges, &c.

(3) *The Total Weight of Purifier Cover* (*in tons*).

This is likewise best obtained from the actual particulars of the cover, as the weight necessarily varies considerably with the design, depth, &c. A rough approximation, however, to the weight is 1 ton for every 100 square feet of area of top. Thus, a cover having an area of 1000 square feet would weigh about 10 tons.

(4) *The Weight of the Water in the Lute.*

This is not very much. Multiply the depth of the lute by half the width (both in inches), and by the length round the purifier (in feet), and divide the result by 5180. The answer will be in *tons*.

(5) *The Weight of Purifying Material* (*Lime or Oxide*), *with the Sieves and Bearing Bars.*

It would not be safe to take, as an average, more than 5 feet all round as resting upon the sides of the purifier; the remainder being supported by the standards. To get the total pressure in *tons*, multiply the length round the purifier by the number of tiers of sieves; then divide the result by 20 for lime, and by 4 for oxide.

Notes.—In testing a purifier, probably there would not be any purifying material in it; consequently, if it is to be tested to the full pressure, it must be made strong enough without any assistance from this source.

It is obvious that it is impossible to give a rule for the weight due to the purifying material, &c., to suit every case, as it depends upon the quantity; but the foregoing is approximate, and has been adopted in the examples given further on.

The "length round the purifier" has been taken round the inside of the side plates. This is not strictly correct, but sufficiently near.

The sum of all these five resistances must be subtracted from the total upward pressure or lifting force. The difference (if any) will be the amount of lifting force to be resisted in some special manner; otherwise the bottom plates will be destroyed.

All that is required to withstand this resultant lifting force is a few holding-down bolts well anchored into the foundations, and spaced at equal distances apart around the outer edge of the purifier. Of course, a sufficient weight of foundations must be commanded by the bolts, to withstand the upward pull they are required to resist. If, however, the purifier rests upon joists or girders, the outer edge should be firmly bolted to those joists which run across and under the purifier. The girders would then form a great resistance to the bulging out of the bottom plates.

Note.—In any case, the girders must be strong enough to resist the bulging of the bottom from *pressure* of gas, irrespective of the dead weight of the purifier they have to carry.

A few examples will make the foregoing remarks quite clear.

It is required to determine whether holding-down bolts are necessary for a purifier 20 feet square, 5 feet deep, with lutes 2 feet deep by 6 inches wide; and, if so, what upward pull they will have to resist.

The total lifting force is—

$$20 \times 20 \times 24 \times 0{\cdot}00233 = \text{(say) } 22 \text{ tons.}$$

The resistances are—

(1) Pressure on bottom	$= 20 \times 4 \times 3 \times 24 \times 0{\cdot}00233$	$= 13{\cdot}4$ tons
(2) Weight of sides	$= 20 \times 4 \times 2 \div 20$	$= 8{\cdot}0$,,
(3) Weight of cover	$= 20\frac{1}{2} \times 20\frac{1}{2} \div 100$	$= 4{\cdot}2$,,
(4) Weight of water	$= 24 \times 3 \times 20 \times 4 \div 5180$	$= 1{\cdot}1$,,
(5) Weight of lime	$= 20 \times 4 \times 5 \div 20$	$= 20{\cdot}0$,,
Total		$= 46{\cdot}7$ tons.

Showing clearly that no holding down is required, even if the weight of purifying material be omitted.

Now take a purifier 30 feet square, the same depth of side plate, but the lute to be 6 inches deeper.

The lifting force equals—

$$30 \times 30 \times 30 \times 0{\cdot}00233 = \text{(say) } 63 \text{ tons.}$$

The resistances are—

(1) Pressure on bottom	$= 30 \times 4 \times 2{\cdot}7 \times 30 \times 0{\cdot}00233$	$= 22{\cdot}12$ tons.
(2) Weight of sides	$= 30 \times 4 \times 2{\cdot}1 \div 20$	$= 12{\cdot}60$,,
(3) Weight of cover	$= 30\frac{1}{2} \times 30\frac{1}{2} \div 100$	$= 9{\cdot}30$,,
(4) Weight of water	$= 30 \times 3 \times 30 \times 4 \div 5180$	$= 2{\cdot}10$,,
(5) Weight of lime	$= 30 \times 4 \times 5 \div 20$	$= 30{\cdot}00$,,
Total		$= 76{\cdot}12$ tons

This shows that for the above purifier no bolts are required to keep the sides down, under the greatest pressure that can possibly be put upon it when in action; but it would not be safe to test it to the full pressure before putting the lime in, as it would certainly lift at the sides, and in all probability fracture the bottom plates.

As another example, take a still larger purifier—say 40 feet square, 6 feet deep, lutes 36 inches by 8 inches, six tiers of sieves for lime.

The lifting force will equal—

$$40 \times 40 \times 36 \times 0{\cdot}00233 = 134{\cdot}2 \text{ tons.}$$

The resistances will be—

(1) Pressure on bottom	$= 40 \times 4 \times 2{\cdot}7 \times 36 \times 0{\cdot}00233$	$= 36{\cdot}2$ tons.
(2) Weight of sides	$= 40 \times 4 \times 3 \div 20$	$= 20{\cdot}4$,,
(3) Weight of cover	$= 40 \times 40 \div 100$	$= 16{\cdot}0$,,
(4) Weight of water	$= 36 \times 4 \times 40 \times 4 \div 5180$	$= 4{\cdot}4$,,
(5) Weight of lime	$= 40 \times 4 \times 6 \div 20$	$= 48{\cdot}0$,,
Total		$= 128{\cdot}6$ tons.

Showing a resultant lifting force of about 6 tons when the purifier is charged with lime, but more than 50 tons if the purifier is to be tested to 30 inches of pressure before the lime, &c., is put in. The bottom plates might stand the 6 tons extra strain, but they would certainly yield under the 50 tons. Therefore holding-down bolts must be used, or the purifier must not be put to the full test till after charging. In the above example the weights are for the most part very heavy. If lighter side plates and cover were used, and fewer tiers of sieves, it is evident that holding-down bolts would be necessary under any circumstances.

Local Strains on the Bottom Plates.

Unless the flanges on the bottom plates are *internal*, and bed all over the

bottom upon the foundations, each of the plates will be subjected to strain, independently of the lifting of the sides, and must be considered as a plate supported all round, and subject to a uniform pressure.

The following formulæ apply :—

For *square* plates, $\dfrac{\sqrt{d \times l^2}}{30} = t.$

For *rectangular* plates, $\sqrt{\dfrac{l^4 \times b^2 \times d}{7200\,(l^4 + b^4)}} = t,$

As the second formula is clumsy, the following approximation may suffice (it errs on the safe side) :—

$$\frac{\sqrt{d \times b^2}}{27} = t.$$

If, however, the plate is almost square, it will be best to use the formula for square plates.

If it is wanted to determine the *span*, a square plate can be made of a given thickness; then $\dfrac{36\,t}{\sqrt{d}} = l.$

In the above formulæ—

d = depth of purifier lute in inches.
l = length of plate in inches.
b = breadth of plate in inches.
t = thickness of plate in sixteenths of an inch.

These formulæ allow the material to be strained to only about 1 ton per sq. inch. The thickness, however, should never be less than $\frac{5}{8}$ inch, for practical reasons.

The better plan is to have the flanges inside; for although with flanges underneath there is the advantage of a clear floor to the purifier, yet there are many disadvantages. They are not so easy to get at to fix the bolts; the plates are not so easy to extract if by chance one should be broken; they are not so strong to resist the lifting of the sides as when the flanges are uppermost; they do not bed so well on the foundations, as they are only supported at the flanges; and to have the purifier the same depth inside, the side plates must be some 3 or 4 inches deeper than with internal flanges.

In concluding this article on the bottom plates, it may be mentioned that the

above rules are as applicable to *round* as to rectangular purifiers, except, perhaps, that there is a little more resistance offered by the bottom plates in the round purifier. For all practical purposes, however, they may be treated alike.

Part II.—THE STRAINS ON THE SIDE PLATES.

The side of a purifier may be looked upon as the side of a shallow box subject to great internal pressure. The strains upon the side plate are due (1) to the great upward lift of the cover, owing to the pressure of gas over the entire top, and the correspondingly great resistance acting downwards; (2) to the pressure of gas acting directly upon the side plate; and (3) to the pressure of water acting horizontally upon the front of the lute.

The first of these forces produces great tension in the side plate, coupled with a tendency to open out the corners of the lute and straighten the side, as shown in the accompanying diagram, fig. 1. The two latter forces produce a bending strain

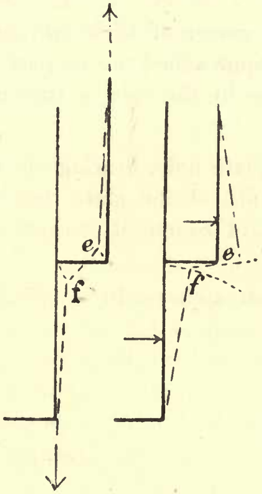


Fig. 1. Fig. 2.

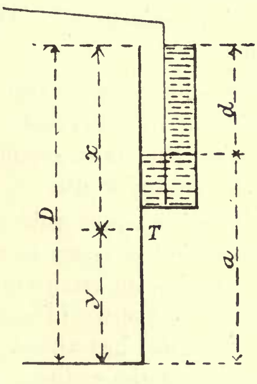


Fig. 3.

tending to break the side as a beam, as well as to rack the corners of the lute, in the manner shown in fig. 2.

The side of a purifier is supported along the top edge by the purifier cover; along the bottom edge, by the bottom plates; and the two ends, by the adjacent sides.

Note.—The cover can only support the side through the grip of the fasteners. This, however, is quite sufficient, as the great upward pull causes much more frictional resistance to the plate sliding out than is necessary to withstand the side pressure.

But if the side of a purifier be very long compared with its depth (as it would be in a very large purifier), no account can be taken of the support at the *ends*, for the simple reason that the deflection transversely or across the plate, due to the side pressure, would have to be so great that the plate would break long before sufficient deflection took place in the other direction to throw any pressure upon the two ends.

This may be proved by finding the breaking strain by the formula for a long oblong plate supported all round the edges, and then comparing it with the result obtained by considering it as simply supported on two sides. The results will be found almost identical.

Note.—I am aware that the bottom of the lute stiffens the side a great deal, and, as it were, acts the part of a long stiffening girder, and therefore would not deflect so much as the thin plate before it could be said to offer resistance. Still, even then, in a very long side, such as 40 feet, a girder 7 or 8 inches deep running its entire length could offer but very little support to the middle plate in the side.

Those plates nearest the ends get support by reason of their connection with the adjacent sides; but as the centre of the side is approached the support becomes less and less, till it is practically *nil*. The middle plate in the side is therefore the most severely strained.

For the foregoing reasons, then, the middle plate only, bearing its share of the forces, is considered in this article. Also the width of the plate has been taken at 5 feet; this being the most common size. But, of course, it is easy to modify the formulæ, &c., to suit any width.

The following is a simple rule or formula which can be readily applied, and is sufficiently accurate for all ordinary purposes. It has been tested by a much more exact method of determining the strains on the side plates, and was found to be very approximate. The exact method would be much too tedious and abstruse for ordinary purposes, especially as experience has already determined the best proportions and strength of side plates for any of the ordinary sizes. It is only in very large purifiers that it would ever be found necessary to calculate the strains.

Formula to find the Strain on a Side Plate of a Large Purifier.

Referring to fig. 3 (p. 107), let—

d = head of water in lute, corresponding to pressure.

a = height of inside level of water from the bottom of purifier.

x = depth from top of lute to point where the strain is required; the weakest point is (say) 3 inches below the lute.

y = distance from this point down to bottom.

D = total depth of purifier.

C = constant, varying according to the section of plate, and to be obtained from the table below.

P = total upward pull of cover. This may be taken as equal to the area of the cover (top) in square feet, multiplied by the pressure of gas in hundredweights per square foot; then deduct the weight of the cover itself, and divide the result by the number of fasteners.

S = strain upon plate in hundredweights.

Then—

$$S = P + \frac{(0{\cdot}01 \times a^2 d\, x) + (0{\cdot}006 \times d^3 y)}{D \times C}$$

After finding S, it must be compared with the resistance to rupture R in the following table, opposite the proper section of plate. Then, if S is more than one-sixth of R (supposing d to have been taken as the ordinary working pressure), or if it exceeds one-fourth of R (taking d as being equal to the depth of lute), then the section is not strong enough as it is, and either a stronger section should be substituted, or ties should be put in the purifier from side to side.

Thickness of Plate.	Size of Flange.	Constant C.	Resistance R.
In.	In. In.		
$\frac{3}{4}$	$3\frac{1}{4} \times \frac{7}{8}$	2·527	635
$\frac{3}{4}$	$2\frac{3}{4} \times \frac{3}{4}$	1·920	572
$\frac{5}{8}$	$2\frac{3}{4} \times \frac{3}{4}$	2·070	473
$\frac{3}{4}$	$2\frac{1}{2} \times \frac{3}{4}$	1·740	546
$\frac{5}{8}$	$2\frac{1}{2} \times \frac{3}{4}$	1·840	461
$\frac{5}{8}$	$2\frac{1}{4} \times \frac{3}{4}$	1·580	443

Notes.—In this table the size of the flange does not include the thickness of plate, but the projecting part only. The constant C is the centre to centre of the resistances to compression and tension for the different sections. In the formula all dimensions must be taken in *inches*, unless otherwise stated. The forces acting upon the plate have, with the exception of P, been embodied in the formula in the terms of the head of water d. It may be added, in explanation of the formula, that $\frac{0{\cdot}001 + a^2 d\, x}{D\, C}$ gives the strain due to the pressure of *gas* on the side; and $\frac{0{\cdot}006 \times d\, y}{D\, C}$ the strain due to the pressure of *water* on the side of the lute. P, S, and R are each expressed in hundredweights.

An example should make the above quite clear.

Let $d=24$in., $a=36$in., $x=33$in., $y=27$in., D=60in., C=2·07in. (for plate $\frac{5}{8}$ in. thick, flange $2\frac{3}{4}$ by $\frac{3}{4}$in.), P=(for a purifier 30 feet square) say 34 cwts.

$$\text{Then } S=34+\frac{(0{\cdot}01\times36^2\times24\times33)+(0{\cdot}006\times24^3\times27}{60\times2{\cdot}07}=134$$

This compared with the resistance R = 473 gives 3·53 as the factor of safety. If, then, 24 inches be the ordinary working pressure of the purifier, it would be advisable to strengthen the side by introducing ties. For this purpose the bearing bars can be utilized.

In conclusion, the following remarks may be worthy of special notice:—It is often thought that the weakest point in a side plate is at the outer angle of the lute; but it is not so. It can be proved, indeed, to have but very little strain upon it. By referring to figs. 1 and 2, it will be seen that the effect of the vertical forces, as regards the racking of the outer corner, is met by the horizontal forces tending to rack the corner in the reverse direction. In fig. 1 the angle e is obtuse, but in fig. 2 it is acute.

The most oppressed part of the plate is undoubtedly just below the inner angle of the lute (see T, fig. 3). This is likewise evident by a glance at figs. 1 and 2. The angle f in both cases being obtuse, shows that the strain on the inner angle of the lute, produced by the horizontal and vertical forces, is of like kind; and, therefore, instead of having a contrary effect, they help one another. It is well that it is so, as the plate can be strengthened in this place by strong, deep brackets under the lute.

Remarks on Round Purifiers.

The strains on a round purifier of the same depth are much less than on a rectangular one of the same capacity.

It may be treated, for the horizontal forces, like an ordinary circular tank. The vertical forces cause tension in the plate vertically, and at the same time throw a compressive strain horizontally, due to the plate resisting any inward pressure as an *arch*.

The above added to the *weight* being less, form perhaps the only advantages of a *circular* purifier.

On the other hand, there is much to be said in favour of rectangular purifiers; for it must be remembered that it would be impracticable to cast a round purifier 6 feet deep and 3 feet lutes of less thickness than $\frac{3}{4}$-inch, although $\frac{1}{2}$-inch might do if merely standing

the strain was all that had to be considered; indeed, it would rarely happen that the *thickness* or weight of a side plate for a round purifier would be *less* than for a rectangular one of the same capacity; but there would be less of them.

In a round purifier the bottom plates are awkward to make, especially if they have planed joints and so many different patterns required.

The work of planing the sides, as well as the bottom, is also more.

The cost of making the patterns for the side plates is more, owing to the curved form.

It is difficult to fit together, to make the circumference exactly right to suit the bottom plates and make the holes come in.

The sieves are all sizes and shapes, and the position of the lugs on the side plates for carrying the bearing bars are almost all different, and so necessitates much alteration to patterns.

The bearing bars are of *odd lengths*.

A row of round purifiers require a much larger house than a set of rectangular purifiers of equal capacity—owing to the vacant corners between them.

The lifting gear must also be wider; and if a fixture to the purifier, it is more expensive.

The work is much more expensive in the round cover than in the simple rectangular one, although the former may be lighter.

PART III.—THE STRAINS ON THE COVER.

Purifier covers are of such variety that it is scarcely possible, within the compass of the present paper, to deal separately with every form of construction. The subject is therefore treated somewhat generally; but the few examples that are noticed in particular may, with judgment and a little modification, be sufficient to indicate the method of finding the strains on any other cover of a different design and shape.

Covers may be classified as follows:—(1) As regards general form, they may be either square, rectangular, or round. (2) The top sheeting is either riveted to the rafters or loose. (3) The top is either flat, arched, pyramidical, or spherical. (4) The rafters and trussing may be either outside or inside the top sheets, or partly out and

partly in. (5) The cover is held down at close intervals all round, or only at the corners. (6) It is lifted either from the two sides or ends, or from the centre.

I can do little more than indicate in outline the course to be pursued in determining the strains, which it is evident vary according to all the varying conditions mentioned above.

There are two positions to which all covers are subject, and which set up entirely different strains—viz., (1) when the cover is fastened down and the pressure of gas is upon it; (2) when the cover is lifted and held in suspension from one or more points.

The form of cover most frequently adopted for very large purifiers is the square or rectangular, having an *arched top* thus—

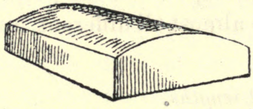


FIG. 1.

Strain on Top Sheeting and Curb.—If the sheeting be loose—*i.e.*, attached to the curb only—the tensile strain on the sheets, as well as the pull on the curb, can be found by the following formula :—

$$\frac{(a^2 + b^2)\, p}{2b} = S \qquad (1)$$

Where S = the actual tensile strain per lineal foot in pounds.
a = half the span of cover in feet.
b = the rise of arc in centre in feet.
p = the pressure of gas in pounds per square foot.

Note.—It will be found that the strain is considerable, especially if the full depth of the lute be taken as the pressure; and it depends very much upon the "rise" of the arc (b). The greater the rise, the less will be the strain upon the sheeting and curbs.

If the *safe strain* (S) on the sheets through the joint has been fixed upon, and it is required to know the minimum rise (b) that can be given to the cover without exceeding this strain, the following formula will determine the rise :—

$$\frac{S - \sqrt{S^2 - a^2 p^2}}{p} = b \qquad (2)$$

If the rise (b) and safe strength (S) be known, and it is required to find the *maximum span* ($2a$) without exceeding the strength of the sheets, then—

$$2\sqrt{\frac{2b\,S - b^2 p}{p}} = 2a \qquad (3)$$

Strain on Curb.—As before stated, it can be found by formula 1, which gives the pull per foot of length. This multiplied by the length of side would give the total pull for the entire length.

It can be resisted (1) by making the curb strong enough to resist the transverse strain as a horizontal girder the full length of the cover, independently of any assistance from rafters, &c.; or (2) it may be made strong enough to resist the pull *between* two *rafters or struts* only; or (3) the strain may be divided between both rafters and curb.

The first plan would be too heavy and costly. The second would not do, as the curb would not stand the strain upon it when the cover is lifted. Therefore the third plan is best; although, perhaps, it is advisable to make the struts or rafters strong enough to take the entire pull, and make the curb equal to the strain upon it when the cover is lifted.

Strain on Rafters.—The rafters act the double purpose of supporting the sheets when required, and of struts to prevent the top curb pulling in. A mere T-iron trussed with light rods, although amply strong enough to carry the weight of the top sheets, is certainly insufficient to resist great end-thrust.

The exact amount of thrust is the horizontal component (c) of the pull of the sheeting at the curb, as shown by fig. 2—

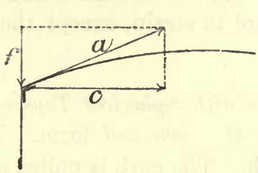


FIG. 2.

Here f is the holding-down force; a is the pull of sheet—viz., S (formula 1) multiplied by the space *between* the rafters (in feet). The resultant force on the rafters

is *horizontal* (c), not inclined upwards; consequently, with an arched T-iron only, there is great tendency to bend upwards thus—

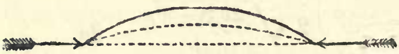


FIG. 3.

In a large cover, a series of strong double-flange girders should be put across, having either a thin web-plate or close cross-bracing. These should be further stiffened by purlins running at right angles to them along the top, and secured to each. There should also be ties connecting all the bottom flanges of the girders running from end to end of the cover, to prevent them twisting out of shape sideways. The bottom flange should be stronger than the top one, as it takes the direct horizontal thrust.

When the *sheeting is riveted down to the top framing*, the strains are quite different. The curb is then relieved of almost all the strain; there being scarcely any pull upon it, unless the rafters bend upwards and pull it in. There is no end thrust upon the rafters from the pull of the sheeting. They act as a long girder, uniformly loaded, and may be treated as such by the ordinary formulæ. The bottom flange should be stronger than the top one, because the top one obtains strength from the sheeting being attached to it. The distributed load is the pressure of gas per square foot multiplied by the length of rafter and by the space between them; and the weight of the rafter and the area of sheeting over it should be deducted from this, to give the exact total distributed load on the rafter. The load acts upwards.

The *strain on the top sheets* depends upon the distance *between* the rafters, and the amount the sheets will bulge upwards under the pressure. In this case the top assumes a series of little arches; the *rise* of each being very slight. Formulæ 1, 2, 3 will solve all questions with regard to strain, except that a must be taken as the distance between the rafters.

Square or Rectangular Covers with Spherical Tops.—Sometimes the top is arched both ways. It then approaches the *spherical* form. There is probably a little less strain upon the sheeting and curb. The curb is pulled at on all four sides, to an equal extent; whereas only two sides of the arched top cover get the bulk of the strain. This form of cover is well adapted for lifting in the centre. It is obvious that this cannot be done with the crown arched only one way. There are *corner* rafters as well as cross ones in large purifiers. Perhaps the greatest objection to this shape is the difficulty of construction; the rafters having to be bent to various and varying arcs,

and it is awkward for sheeting. The top cannot be made the true surface of a sphere without *arching all the four sides*, which, of course, is never done.

The strain on the sheeting may be found as follows:—

$$\frac{(a^2 + b^2 p)}{4 b} = S \qquad (4)$$

$$2 S - \frac{\sqrt{2 S^2 - a^2 p^2}}{p} = b \qquad (5)$$

$$2 \sqrt{\frac{4 b S - b^2 p}{p}} = 2 a \qquad (6)$$

In the above formulæ, a must be taken as half the distance *across the corners* of the cover. All the other letters are as before employed.

Round Purifier Covers.—Formulæ 4, 5, and 6 are applicable to the spherical tops of *round* purifier covers. In a round cover the rafters are arranged radially, meeting in the centre, similarly to a gasholder top. The pull of the sheets is easily resisted by a strong top curb, the compressive strain on which is given by the formula—

$$\frac{(a^2 - b^2)\, p D}{8 b} = C \qquad (7)$$

Where D = diameter of cover, in feet.
C = actual compressive strain on the section, in pounds.

The curb row of plates aid the top curb in resisting compression. There is very little end-thrust upon the rafters in such a case—their duty being to support the sheets when the purifier is out of use, and there is no pressure within, and to take also the bending strain due to lifting the cover in the centre. If, however, the sheets are riveted to the rafters, there is considerable bending strain upon them, due to the transmitted pressure of gas.

It must be noted that the pressure on the rafter from this cause is not uniformly distributed. The pressure in the centre is *nil*, and gradually increases as it nears the curb, thus—

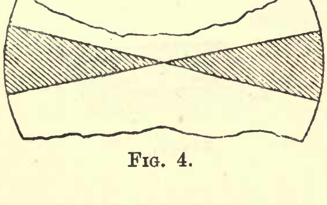


Fig. 4.

The strains caused by lifting in the centre are considerable. Diagonal rods taking hold about half-way down the rafters, and meeting together in the middle, are perhaps the best plan. (See fig. 5.)

The strain is somewhat complicated. There is bending at A and A; between A and B there is tension; and from A to C there is compression. The rafter must be

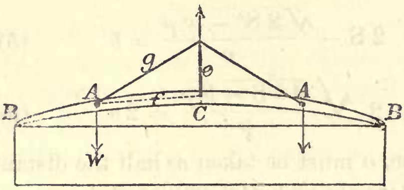


FIG. 5.

trong enough at A to resist the bending due to the weight of the sides acting at the end of a cantilever A B long. The attachment to the curb at B must be strong to resist the pull.

$$\text{The thrust on A C} = \frac{w f}{n e}$$

$$\text{The pull on the lifting-rod } g = \frac{w g}{n e}$$

Where w = total weight of cover
n = number of lifting-rods.

There should be several lifting-rods; and, in determining the section, not more than 3 tons per square inch should be allowed, as it is difficult to get all the rods to take an equal share of the work.

Flat Tops.—If a cover has a flat top, or is made up of a series of flat surfaces, when the pressure comes upon them they will swell out. The rise they will assume can only be guessed at, as it depends so much upon the slackness of the sheets and the extent of the unsupported area.

In a square cover with loose flat top, formula 4 can be used; assuming a reasonable rise, and taking a as being equal to half the distance across the corners. If the top be pyramidical, thus—

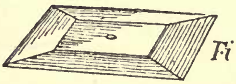


FIG. 6.

each of the surfaces can be treated separately, taking the rise and span as judgment directs. This latter form is excellent for covers up to about 24 feet square, and lifted in the centre.

Outside Rafters.—Some covers have the rafters outside, in which case the sheets are always riveted to them. An advantage is that there is very little strain on the rivets. Perhaps the chief objection is that they make the cover deeper over all, and so require more lifting space.

Strains on the Sides of Covers.—The sides are not only subject to severe strain when lifted, but also from the pressure of the gas when at work. Fig. 7 regresents the side under pressure—

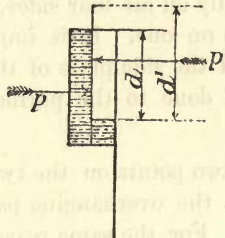


Fig. 7.

In this figure, p is the pressure of water on the outside, acting at two-thirds the distance from the top of d; p' is the resultant pressure of the gas on the inside, acting at half the distance, d'; p' is equal to the length of the side, multiplied by the depth d' (both in feet), and the pressure of gas per square foot in pounds. This is met by the pressure of water on the outside (viz., $\frac{d^2}{2}$ multiplied by length of side and $62\frac{1}{2}$), and the resistance of the side to bending outwards. Then p, multiplied by its distance from the top curb, must be subtracted from the moment of p' about the same point; and the result will be the bending moment outwards.

Though this bending moment is slight in most cases, yet, when the cover is a large one with deep lutes and high pressure, it has a strong tendency to bend the bottom edge outwards. The ways of resisting this are as follows :—(1) Strong *bead* or bottom curb. (2) Thick side plates, well attached to the top curb all along. (3) Ties running right across the cover, connecting the *arched ends*, as low down as the side plates will admit of. (4) Wedging tightly down by fasteners, so as to cause frictional resistance, at the

bottom of the lute, to slipping out. (5) Vertical stiffeners or uprights firmly fixed to the top curb and top sheets, and riveted to the sides and bottom curb. These stiffeners are most essential in a very large cover, to preserve the side from twisting when the cover is lifted, as well as for the above purpose.

Fasteners should be placed as close together as convenient. Having only a few fasteners is bad, as it not only throws great strain upon the cover and the fasteners themselves, but also upon the purifier; and this, being of cast iron, should not have the strain concentrated in a few spots, but distributed uniformly all round. The lift on *one* fastener, when they are placed at equal distances apart for a cover arched *one* way, is equal to the total upward lift of the cover divided by the number of fasteners on the two *sides* only. The end fasteners have much less strain. If the cover has a spherical top, or one sloping equally on all four sides, the total lift may be divided by all the fasteners, to get the strain on one. It is important that fasteners should be very strong, and take well hold of the side plate of the purifier, because if a few fail, a great deal of damage may be done to the purifier plates by the others breaking away.

Lifting should be done from two points on the two ends of a rectangular purifier, in preference to the two sides; as the overhanging part is shorter, and consequently there is less strain upon the side. For the same reason, the lifting eyes should be as far apart as possible, The strain may be found by treating it as a girder supported at the centre, uniformly loaded, and with the weight of the sides of the cover hanging on the extremities.

The cover is frequently lifted in the centre; in which case it is best to have long truss-rods from each corner, and meeting in the centre with a truss-cup or bolt. The

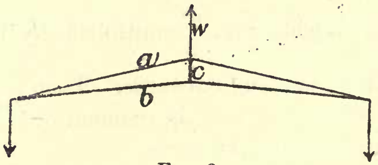


FIG. 8.

cover should have corner rafters. The strain on the rods and rafters can be found thus—

$$\text{Strain on rod} = \frac{w\,a}{4\,c}, \text{ tension,}$$

$$\text{Strain on rafter} = \frac{w\,b}{4\,c}, \text{ compression,}$$

where w = weight of cover, and a, b, and c the length of each respectively. (See fig. 8.) It will be noticed that there is considerable strain upon the corner rafters. This is, however, partly met by the top curb. When there are no corner rafters, the compressive strain is split up in two directions (at each corner) along the top curb. When a cover is lifted from the centre in this way, there is less strain upon the sides, as they are supported at each end, and only have to carry the intermediate uniform load.

In conclusion, it must be borne in mind that, although the formulæ, &c,, contained in these articles provide for the *actual strains* upon the structure, yet it may be necessary, for other and well-known practical reasons, to increase the sectional areas and thicknesses, in some instances, beyond that which would be required merely to resist the strains.

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FLEET STREET, E.C.